TAMPEREEN TEKNILLINEN YLIOPISTO

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POTENTIAL OF WAVE POWER: A TECHNO-ECONOMIC FEASIBILITY ANALYSIS OF GYRATION BASED WAVE ENERGY TECHNOLOGY

Master of Science thesis

Examiner: Prof. Juho Kanniainen
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Tuotantotalouden koulutusohjelma

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Aaltovoimaenergian kehitys on ollut hidasta ja suurimmat taloudelliset tukijat ovat olleet valtioita ja unioneja, kuten EU. Aaltovoiman kehittäjät ovat pääsääntöisesti pieniä, yksityisiä startup-yrityksiä ja yksityisten sijoittajien osuus rahoituksessa on ollut pientä. Tämän diplomityön tavoite on arvioida aaltovoiman taloudellista potentiaalia, sekä arvioida, voiko aaltovoiman kehitys tapahtua kannattavasti yksityisin sijoituksin. Yhteenvetona voidaan todeta, että aggressiivinen investoiminen aaltovoimaan on liian riskialtista yksityisille sijoittajille. Lisäksi todetaan, että saavutettavissa olevat sähköntuotannon kustannukset tulevat olemaan liian korkeita kaupalliseen käyttöön lähitulevaisuudessa.

Kannattavuuden kehityksen arvioiminen perustuu oppimispohjaisen menetelmän käyttöön ja sähköntuoton tehokkuuden kasvuun. Sähköntuotantotehokkuuden kehitys perustuu laitteeseen osuvan energian talteenoton hyötysuhteen kasvun, sekä käyttöasteen kehityksen kautta. Investointien kannattavuutta arvioidaan reaalioptiolähestymisellä. Tätä varten on suunniteltu 15 vuoden laiteasennusohjelma, jossa on kaksi kasvuoptiota. Nettonykyarvo tälle skenaariolle saadaan hyödyntämällä päätöspuu mallintamista. Käytetyt taloudelliset indikaattorit ovat nettonykyarvo (net present value, NPV), sisäinen korkokanta (internal rate of return, IRR) ja sähköntuotannon kustannus (cost of electricity, COE). Työssä referenssinä käytetty aaltovoimageneraattori on Wello Oy:n kehittämä Penguin konsepti.

ABSTRACT

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Wave power development has been slow and financed mostly by public support of different countries and unions. The development has been carried through by small developers and financial support of the private sector has been small. The aim of this thesis is to estimate the future potential of wave power and whether it has the economic potential to an extend that the development could be carried out by private investments. The conclusion is that wave power is too risky for any aggressive private investments and the future cost of electricity (COE) levels seem too high for commercial use.

The future feasibility estimations are based on a learning curve method and the energy capture efficiency improvements. The energy capture development is modelled by the wave energy converter (WEC) capture efficiency improvements and robustness improvements. A 15 year installation scheme is made to estimate the investment feasibility and a real options approach is made by applying a decision tree model. The economic indicators used in this work are net present value (NPV), cost of electricity (COE), and internal rate of return (IRR). The main reference wave energy converter (WEC) is the Penguin by Wello Oy.

PREFACE

This master thesis is written as part of Industrial Engineering and Management studies at Tampere University of Technology. Most of the work of this thesis was done in Trondheim, Norway, at the Norwegian University of Science and Technology. I would like to thank Prof. Stein-Erik Fleten for the instruction and for making my visit at NTNU possible. I would also like to thank my supervisor Prof. Juho Kanniainen of TUT.

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Jesse Turkia

CONTENTS

LIST OF ABBREVIATIONS

BCOE	Basic Cost of Electricity
CAPEX	Capital expenditures (Includes O&M and Insurance)
CIWHL	Cut in Wave Height Limit
BCE	Basic Cost of Electricity
COE	Cost of Electricity (After chapter two term COE is used for the levelised cost of electricity)
DCF	Discounted Cash Flow methods
FCC	Future Cost of Cash
FIT	Feed in Tariff
GHG	Greenhouse Gas investigation
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
IC	Initial costs (CAPEX + pre operational costs)
IRR	Internal Rate of Return
LCOE	Levelised Cost of Electricity
OPEX	Operational Expenditures (all costs created during WEC use)
WEC	Wave Energy Converter
WECIC	Wave Energy Converter Initial Cost (cost of only the converter)

1. INTRODUCTION

Global energy consumption will grow by 30 % from 2010 level, by the year 2040 according to Exxonmobil (2012). Given that the traditional energy resources are finite; this creates a demand for renewable and alternative electricity energy sources. Solar -and wind power are highly established methods due to great development efforts during the last three decades. Another intriguing option, with practically unlimited resource, is wave power. The accessible wave energy, just in Ireland, has been calculated to be as high as 20.76 TWh/year or 80 % of its 26 TWh electricity demand (Ferrell et al. 2015).

Wave energy has certain benefits compared to other renewable energy production methods, but there are still many problems that need to be solved before it can prove functional for commercial use. Some of the crucial problems are poor power capture efficiency, robustness issues and the fact, that wave power is considered expensive. Wave energy technology is still three times more expensive than offshore wind energy and it is about ten to fifteen years behind in development (Astariz & Iglesias 2015). The development is undertaken by small private companies with limited funding (EMEC 2015a). For wave energy to reach the commercial state it needs steady funding and the development need to be more focused.

The existing research mostly tries to estimate the current costs of wave energy or the future costs with some minor improvements (Dalton et al. 2010, O'Connor et al. 2013a, Astariz & Iglesias 2015 and Farrell et al. 2015). Most of the existing research is based on Pelamis P1 wave energy converter (WEC), which suffered bankruptcy in 2014. Pelamis P1 has been the only converter with a published power matrix and has therefore been the most studied concept. In this thesis the main reference concept is Wello Penguin wave energy converter.

The goal of this thesis is not only to estimate the feasibility of wave energy after a certain period, but in addition to estimate the economics of a multi-stage installation plan leading to what should be a commercially competitive end product. Wave power development is financed mostly by public subsidies in addition to the available feed in tariffs. This thesis will answer the question whether wave power has the economical potential to be developed feasibly through private and focused investments during the next 15 years.

The future costs are estimated by using a learning based method. To estimate the economics of the total investment a 15 year installation plan is made based on the industry views and the assumption that wave energy is 10 to 15 years behind in development. A real option approach is taken and a decision tree model with growth options is used for this purpose.

This thesis consists of four main chapters in addition to introduction and conclusions. Chapter two is theory and methods, where the main methods used are introduced and described. Chapter three is the background and political context. In chapter three the history of wave power and the main issues and benefits are described. In addition the global wave resource and market size is discussed. Chapter four presents the Wello Penguin converter and the cost creation is described. Chapter five includes the future potential - and feasibility analysis.

2. THEORY AND METHODS

2.1. Power of waves

The power of waves, in deep-sea states, depends on the wave period and the wave height. Equation 1 determines the energy of waves from all directions as

$$P_w(H_s, T_e) = \frac{\rho g^2}{64\pi} H_s^2 T_e, \tag{1}$$

where the power (P_w) is expressed in kW/m, if the significant wave height (H_s) is expressed in meters and the energy period (T_e) in seconds. In addition, ρ is the density of water. (Nielsen & Pontes 2010) Various sources present the periodical time value of waves in the zero crossing period T_z or as the peak period T_p. The relations between these values are:

$$T_e = 1.2\ T_z \tag{2}$$

$$T_e = 0.857\ T_p. \tag{3}$$

The energy of waves in a certain location can be calculated by multiplying the hourly amount of a certain wave condition (scatter plot hours) with equation 1. (Nielsen & Pontes 2010).

2.2. Availability

Availability is defined as the amount of time when the device is producing usable power. A number of factors, such as device reliability and the device's ability to be accessible, effect on the availability. Accessibility is defined as the percentage of the time when the machine can be accessed for service. The limiting value of accessibility is normally the wave height and therefore a site with greater resource has typically a smaller accessibility **(**O'Connor et al. 2013a). Accessibility can be a crucial variable in the future in high resource areas such as Ireland (O'Connor et al. 2013a). Lack of access is already an issue with offshore wind power in the North Sea, where the access levels of wind farms are typically between 60 and 90 %, based on the wave height limit of 1,5 m **(**O'Connor et al. 2013b**)**. When moving from offshore (50 m) locations to near shore (10 m) the accessibility increases typically by 50 % (O'Connor et al. 2013a). In a survey by PricewaterhouseCoopers (PwC 2011), the offshore operators have reported availability levels between 90 and 97 %. This can be due to more reliable turbines, development in high sea accessibility or overly optimistic estimations. Stated access and availability levels from different sources can be seen in table 1.

Table 1. Summary of typical access and availability levels of onshore and offshore wind.

	Access levels [%]	Availability [%]	Source
Onnshore wind	100	98	Dalton et al. 2012
Offshore wind	60 - 80	70 - 90	Dalton et al. 2012
	60 - 90		O'Connor et al. 2013a
		90 - 97	PwC 2011

Van Bussel (2009) has studied the availability levels of offshore wind power. He has presented an empirically proven equation, derived from Monte Carlo simulation and offshore wind power data, to show the relation between availability and accessibility with certain device reliability. The formula for availability is

$$F_{stormcorr}\,(S_{tormper,}\ \text{Maxavail}) = \left(1 - \frac{S_{stormper}}{100}\right)^{3*\left(1-\frac{\text{Maxavail}}{100}\right)+650*\left(1-\frac{\text{Maxavail}}{100}\right)^{2}}, \tag{4}$$

where $S_{stormper}$ is the percentage of the time when the wave conditions are too high for access and operations. Maximum availability (Maxavail) is the availability of a converter when the access is granted at all times. This number can be obtained as an industry benchmark. Van Bussel (2009) states that 99 % availability for mature technologies and 98 - 87 % for developing technologies are appropriate.

2.3. Costs of electricity

The most commonly used financial indicator for evaluating wave energy viability is the cost of electricity. The cost of electricity can be either (i) basic cost of electricity (BCOE) or (ii) levelised cost of electricity (LCOE). BCOE is a rough estimate of yearly and immediate costs. The common ways to interpret this indicator are:

1. Total initial cost (IC) of the project (including the cost of the WEC) divided by the annual energy yield. This method leaves out the annual costs. (Dalton et al. 2012)
2. IC + Operational Expenditures (OPEX) divided by the annual yield. This will provide an undiscounted COE. (Dalton et al. 2012)

Downside of this technique is that it does not consider the project duration.

Levelised cost of electricity (LCOE) is conventionally defined as the average cost per KWh of useful electrical energy produced by a facility. There are two methods according to Gross et al. (2007) to calculate the LCOE: The "Discounting" and "Annuitizing" methods. In the discounting method, the stream of real future costs and electrical outputs are discounted to their present value using a discount rate. Thus the levelised cost is the ratio of the present value of costs to the present value of outputs. In the "annuitizing" method, the present value of the stream of costs is calculated and converted to an equivalent annual cost by using a standard annuity formula. The dominator is the average electrical outputs per year. If the output and cost are considered unchanged, these methods give the same result. Most of the reference studies that are used in this work use the firs method and thus all the cost of electricity calculations are done with the same method to achieve better comparability.

The formula for Discounted LCOE for a wave farm is

$$\mathrm{LC_d} = \frac{PV\ (Costs)}{PV\ (Output)} = \frac{\sum_{t=n}^{n} C_t/(1+r)^t}{\sum_{t=n}^{n} O_t/(1+r)^t}, \quad (5)$$

where C_t is the annual total cost and O_t is the annual energy output and r is the used discount rate (Gross et al. 2007). The results are normally presented in €($)/MWh or Cents/kWh.

It varies weather the energy sold or subsidies are included in the calculations or not. This and other assumptions such as interest rate and time of the evaluation create difficulties when making the different research data comparable. In this paper the levelised cost of electricity is always calculated without any feed in tariff (FIT) or sales price, since the FIT is an important variable. From this on the term cost of electricity (COE) will stand for the discounted levelised costs of electricity.

2.4. NPV and IRR

Discounted cash flow (DCF) -based methodologies such as net present value (NPV) or internal rate of return (IRR) are widely used in the literature and they do give a usable estimation on what to expect from an investment (Farrell et al. 2015).

The formula for the net present value of a power plant investment, according to Dalton et al. (2012), is

$$\mathrm{NPV} = \sum_{n=0}^{N} \frac{AO_n \times FIT_n}{(1+r)^n} - \sum_{n=0}^{N} \frac{[Cost]_n}{(1+r)^n}, \quad (6)$$

where *AO* is the annual electricity output in kWh, *FIT* is the feed in tariff for renewable energy (€/kWh) and *Cost* is the initial cost and the annual costs of the plant or farm. In other words, this approach does not take into account the current sales price of electricity.

In the Dalton et al. (2010) paper a 10 % return rate is suggested for a project to be considered profitable. They state that investors do not use the same indexes, since they take the company exit value into account. Taking the value of the company into account is out of range in this work and therefore the focus will be on the installation feasibility (and the technological maturity). Benchmarking on early stage offshore wind farms a discount rate (for the NPV calculations) of 8 % is suggested by Farrell et al. (2015) and O’Connor et al. (2013a) and according to Dalton et al. (2012) a 6 % discount rate is appropriate for larger installations (>100 MW).

A commonly used measure of the profitability of a potential investment is the internal rate of return (IRR). Internal rate of return is a discount rate that causes the net present value of all cash flows of a particular project to equal zero. Dalton et al. (2010) present the IRR formula for an energy investment as

$$\mathrm{NPV}(0) = \sum_{n=0}^{N} \frac{AO_n \times FIT_n}{(1+IRR)^n} - \sum_{n=0}^{N} \frac{[Cost]_n}{(1+IRR)^n}, \tag{7}$$

where NPV(0) equals zero and *IRR* is the discount rate causing NPV(0).

The cost of cash increases with time due to the consumer price index Dalton et al. (2012). If an investment is done in another year, the value will need to be multiplied with the Future Cost of Cash (FCC) index

$$\mathrm{FCC} = (1+i)^n, \tag{8}$$

where n is the time in years from the reference time and i is the inflation rate. The inflation rate has been small or negative in recent years with different definitions due to the problems in the economy. The Euro area average inflation rate has changed between -0.6 and 0.3 % in 2015 and the average value between 1991 and 2015 has been 2.08 %, which is close to the target value of 2 % set by the European Central Bank (Trading Economics 2015). Also the Euro area producer price index has declined 2.6 % between October 2014 and October 2015 (Trading Economics 2015). Dalton et al. (2012) and Ferrell et al. (2015) have based the cost of cash estimations on the scrap metal indexed since metal is the main material in wave power. Also scrap metal prices have been declining since 2010 - 2011 but during the period 2004 - 2015 the average annual change has been 3.88 % (grade E40) (Eurofer 2015).

2.5. Grid sales revenue

Feed in Tariff (FIT) refers to the minimum guaranteed price per kWh that an electricity producer gets for the electricity fed into the network. It is defined as the full price per kWh received by the independent producer of renewable energy, including the premium above or additional to the market price, but excluding tax rebates or other subsidies. (Dalton et al. 2010**)** Each year’s revenue from FIT depends on two factors: The total energy produced and the electricity tariff rate by the utility company. Notable factor is that the fixed feed in tariff for a certain period is not adjusted with inflation. A feed in tariff remains fixed to a certain monetary value and the annual income will therefore decrease through inflation (Dalton et al. 2012).

2.6. Real options/Growth option

NPV or IRR consider the investment in a static ‘now or never’ context and thus asses the viability of the investment at a single moment in time when used alone. For this purpose a real option approach is taken. In this thesis a multi stage installation plan is being crafted with several growth options.

Trigeorgis (1996, 13 - 14) writes that although in isolation a proposed investment may appear unattractive, it may be only the first in a series of similar investments. If the investments are carried out properly and the commercializing is done right the following projects can prove to be profitable in case of favoring circumstances. He also states that many early investments (such as R&D or pilot projects) can be seen as prerequisites or links of interrelated projects (Trigeorgis (1996, 13 - 14). The value of these early projects are not as much as the direct outcomes but the options for future opportunities that can be unlocked. The future possibilities can be through new-generation products or processes, access to unlocked markets or strengthening the firm’s core strengths or strategic positioning. But unless the initial steps for development are taken the following steps cannot be made. The infrastructure and experience gained can place the firm in a competitive advantage if a learning curve is present. (Trigeorgis 1996, 13 - 14)

2.7. Decision tree

An intuitive approach for using the real options approach for valuating a project can be done by using decision trees. Figure 1 presents basic models for binominal lattice and binominal tree according to Brandão et al. (2005), where *S* is the currents market price (profit/lost) and *q* is the probability of an upwards movement to *Su*.

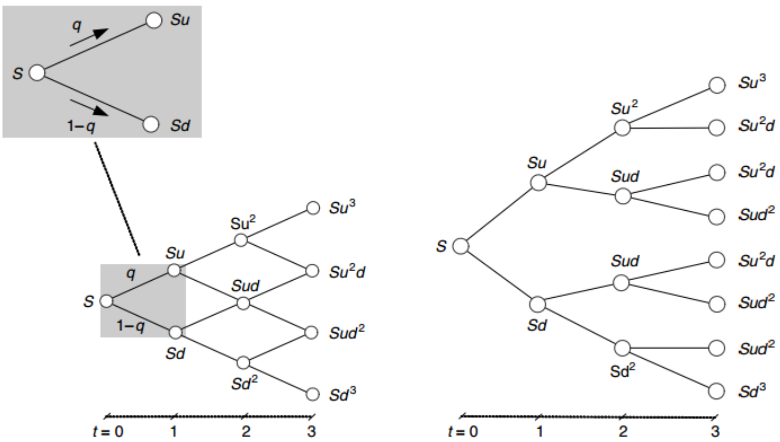

Figure 1. Binominal lattice and corresponding binominal tree (Brandão et al. 2005).

The binominal lattice can be viewed as development scheme with binary change branches, with the feature that the outcome of up-movement followed by down movement causes the same result as down and then up. The binominal lattice can be used to estimate the Black-Scholes-Merton continuous-time valuation model for financial options, with the added advantage that it can be used with early exercise, whereas the Black-Scholes-Merton can only valuate European options. (Brandão et al. 2005) The downside of binominal lattice is that it is not intuitive, especially when valuating real assets with changing conditions throughout the process.

An option for the binominal lattice is the binominal tree. The binominal tree provides more intuitive approach, can contain more simultaneous options and is more flexible with real life conditions. By constructing a decision tree where the nodes present managerial decisions the managerial flexibility can be modelled in a discrete time. (Brandão et al. 2005) With this approach the real existing decisions can be present and when used together with DCF methods more accurate investment viability estimations can be made than with DCF methods alone.

2.8. Learning rate

Future costs can be estimated with learning based methods. An example of these methods is the learning rate method. Using this method means that when the cumulative amount of a certain technology increases the costs drop to a certain percentage with every new installation. This does not give the new COE but only estimates the change of costs.

The learning curve is defined by Neij (1999) as the cost reduction of a standardized product within a single firm, while an 'experience curve' may also describe the cost reduction of non-standardized products on a national or global level (Dalton et al. 2012). The equation for the learning curve is

$$P = N^{ln(lc)/ln2}, \tag{9}$$

where P is the percentage scaling of costs or the "learning factor", N is the number of WEC's installed by a certain company and lc is the 'learning curve factor'.

Since there is no sufficient history data when it comes to wave power, the closest benchmark is the offshore wind power. The calculated offshore wind power learning factor has been between 82 and 90 % during offshore wind power's development time (Dalton et al. 2012). Dalton et al. (2012), and Ferrell et al. (2015) have suggested 85 - 90 % to be an appropriate estimation for wave power applications.

The biggest problem of the learning rate method is defining the growth rate of the installations at such an early stage of the development. Many of the existing feasibility studies have tried to overcome this problem by considering the cost development through bulk discounts. In these research papers such as Dalton et al (2010) and O'Connor et al. (2013a) the authors have assumed that manufacturers can grant bulk discounts with larger installations. The bulk discount method follows similar mathematical formula than the learning curve method (present in equation 9) and goes

$$p = A^{ln(bdf)/ln2}, \tag{10}$$

where p is the percentage scaling of costs, A is the cumulative number of WECs in the wave park and *bdf* is the bulk discount factor. Ferrell et al. (2015) use the same *bdf* and *lc* values. The problem with the bulk discount approach is that it does not give a good estimation for the future costs of wave power, but just for the “next” farm. Therefore the approach used in this thesis is based mostly on the learning rate

When using either of the methods the discount is based on a cumulative sum of the factorial reduction in price. The cumulative equation is

$$IC_{total} = \sum_{n=1}^{N} P_n * IC_1, \tag{11}$$

where IC is the total initial cost allocated to one wave energy converter and IC_{total} is the total cost of a wave farm. P is the percent reduction used in IC costing (Dalton et al. 2010).

3. BACKGROUND AND WAVE POWER OPERATING ENVIRONMENT

Wave energy is not a new idea, in fact it has been discussed for centuries, but yet little attention has been given to it. Earliest indications of wave energy are from the 13th century China, where waves were used to power mills (Lopez et al. 2013). In the 70's, due to the oil crisis, wave power had first time commercial interest in universities and among investors. This enthusiasm ended though in the 80's when the oil price came down. Now again wave power is somewhat current due to CO2 emission regulations and common goals towards cleaner energy. Countries and communities such as EU are supporting the development of renewables including wave power. Still the amount of money is somewhat small and rapid development of technologies has not started. This is due to the uncertainties whether wave power can ever be competitive with other available energy sources.

Different researches and manufactures are agreeing that at this point wave energy cannot compete with any existing technologies and private investors still see wave energy unprofitable for large-scale investments. The literature has also consensus that without considerable FITs any small installation alone could not be profitable in the near to midterm future (Babarit et al. 2012, Dalton et al. 2012, Astariz et al. 2015, Farrell et al. 2015). Therefore public incentives are needed to make the development possible. The investments made by private companies are of small scale and also seen more as investments to product development, with strong portfolio thinking (Astariz et al. 2015, Farrell et al. 2015). This has caused the development to be slow.

3.1. Comparison of wave power to other technologies

Offshore wind power is similar to wave power in numerous ways and it can be considered to be wave power's most important rival. The similarities can be seen in favored locations, operations -and maintenance methods, connection -and mooring methods and cost structures. Neither of them have had any large commercial success to date, even though offshore wind power leads in development by 10 – 15 years (Lopez et al. 2013, O'Connor et al. 2013a).

Although the similarities are clear, Tomasz Mucha (technology manager of AW-Energy) states that wave power is not in a direct competition with other renewable energy methods and instead they can be complementary technologies (personal communications with AW-Energy technology manager Tomasz Mucha). The two methods can be complimentary in the same energy parks and wave converters can be connected to the same grid with offshore wind. This could create benefits through economics of scale and level the annual and momentary output. In addition high wind -and high wave conditions are not automatically found at the same locations (personal communications with AW-Energy technology manager Tomasz Mucha). This being said, since the maximal profit is most often the key driver when choosing energy production methods, these technologies are often seen in a direct competition. In this sense, offshore wind power is the most important comparison when trying to estimate the potential of wave power. When competing on the capital invested another, in many ways, comparable technology would also be tidal power. When wind power is highly established technology, tidal power has not yet reached that stage and therefore it is not clear whether it will prove to be feasible enough for a large scale utilization.

In table 2 are presented estimations for levelised cost of electricity (LCOE) values of different electricity technologies. In 2015 the LCOE of offshore wind power was estimated to be 101.43 €/MWh and for the rapidly growing onshore wind power the value was 67.68 €/MWh. This gives an important benchmark for wave power when estimating its commercial potential. For example Farrell et al. (2015) and Astariz & Iglesias (2015) estimated the LCOE of the Pelamis P1 wave energy converter to fall between 291-581 €/MWh.

Table 2. Estimations of levelised costs of different energy production methods (Astariz & Iglesias 2015).

Technology	Cost [€/MWh]
Wave Power (Pelamis P1)	291 - 581
Onshore Wind	67.68
Offshore Wind	101.43
PWR nuclear	49.96
CCGT (combined cycle gas turbine)	43.17
IGCC coal (integrated gasification combined cycle)	36.59
IGCC coal with CCS (carbon capture and storage)	55.76
Retrofit coal	44.40
Pulverized fuel	32.57
Pulverized fuel with CCS	50.79
CCGT with CCS	59.78

The initial costs of offshore wind investments ranged from 2.35 M€/MW to 3.56 M€/MW in 2008. Costs increased during the 2010 - 2013 period, spanning from 2.73 M€/MW to 4.25 M€/MW (using 2013 exchange rate of 0.7589 from USD to €) (International Energy Agency 2013). The increase in costs resulted from underlying cost increases, reliability concerns and deeper farm locations, while the earlier plants were in relatively shallow waters near the shore (International Energy Agency 2013). Most of the new plants since 2010 are located in water depths exceeding 20 m (International Energy Agency 2013). By the end of 2013 the costs levelled to range from 3.05 M€/MW to 3.34 M€/MW (using

2013 exchange rate of 0.7589 from USD to €) including transmission capital costs. **(**International Energy Agency 2013). This reflects from several factors including a better understanding of the key risks of offshore wind construction and larger projects leading to greater economies of scale. Figure 2 presents cost development estimates for wind power total initial costs. For wave power, or more specifically for Pelamis P1, the IC is estimated to be between 4 and 7 M€ per WEC rated 750 kW (5.3 – 9.33 M€/MW) (Ferrell et al. 2015). This gives an idea where the development of wave energy is at the moment compared to other technologies.

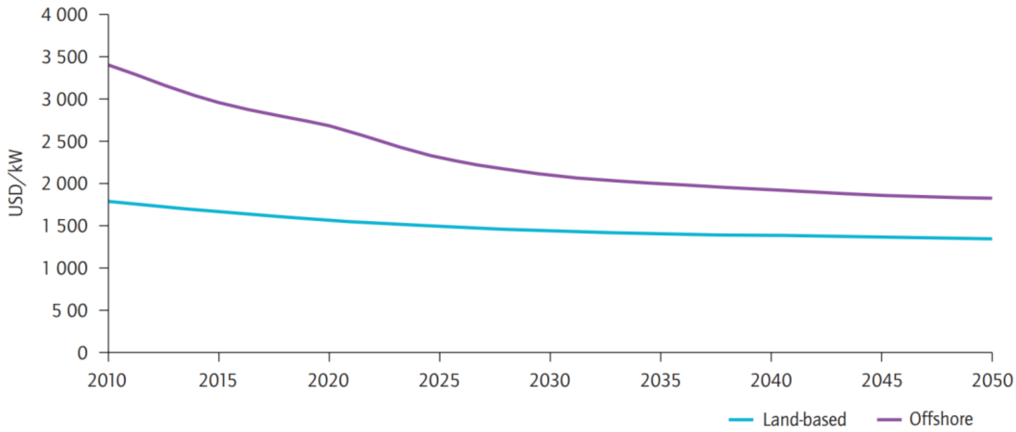

Figure 2. Wind generator total investment cost estimation development (International Energy Agency 2013).

Offshore wind power has a strong support in many countries, mostly in Europe. By 2018 offshore wind power is planned to reach a cumulative capacity of 28 GW, which is a leap of 22.6 GW from 2012 level. The main supporters of offshore wind power are United Kingdom followed by Germany and Denmark. Over two thirds of the planned capacity by 2018 is planned to be in Europe. China, United States, Japan and Korea account for the rest. By 2018 offshore wind should deliver 76 TWh annually**.** (International Energy Agency 2013)

An important actor for wave power development has been Ireland. Ireland's accessible wave energy resource is estimated to be as high as 20.76 TWh/year, or 80 % of its annual energy demand and thus wave energy has been an important part of its renewable energy plan. During the period of 2002 - 2015 some 26.3 M€ of public support has been directed to the development of wave power in Europe. In addition many countries have set plans for wave power development. Ireland has set a FIT of 260 €/MWh starting from 2016 for the first 30 MW of wave power installed. (Farrell et al. 2015) Ireland's Offshore Renewable Energy Development Plan (OREDP) envisages installations up to 1500 MW during the period of 2020 – 2050. As a short goal, Irelands "desire" is to install 500 MW by 2025 and 84 MW by 2020. In addition to Ireland, the Portuguese government has promised a FIT for the energy produced with wave energy. Planned tariffs in Portugal range from

130 to 260 €/MWh, depending on the cumulative amount of WECs installed (Dalton et al. 2010). In addition to this Spain, Denmark and Greece have plans for setting feed in tariffs ranging between 60 and 100 €/MWh (Dalton et al. 2012). These planned tariffs are listed in table 3.

Table 3. Planned and existing Feed in Tariffs.

Country		FIT [€/MWh]	Source[a]
Ireland		260	A
Scotland		350	B
Portugal	Scaled rates		
	1-4 MW	260	C
	5-9 MW	190	C
	21-100 MW	130	C
Spain		60	B
Denmark		80	B
Greece		100	B

[a]A: Farrell et al. 2015, B: Dalton et al. 2012; C: Dalton et al. 2010

3.2. Issues of wave power

So it can be said that wave power has many challenges that need to be overcome before it can become financially profitable or able to compete with more mature technologies. As discussed above, the most important factor for the investor is the feasibility compared to other options. The feasibility builds up from numerous factors and below are listed the main issues that need to be addressed and solved before the technology can compete on the open markets.

- The conversion of the slow, about 0.1 Hz, motion of waves into a useful mechanical motion to be connected to a 50 Hz generator. This to be achieved, some energy conversion stages are necessary: Firstly to convert wave energy to electricity, and secondly to rise the WEC's generated voltage levels to able the energy transmission from the sea to the land and to the power grid. (Dalton et al. 2010, Lopez et al. 2013)
- Waves vary in height and period and their power levels vary accordingly. Yet the electricity output need to be even in short time intervals. This creates one of the essential disadvantages of wave power. There are many different concepts to tackle this problem, but power losses are unavoidable. (Dalton et al. 2010, O'Connor et al. 2013a, Lopez et al. 2013, Astariz & Iglesias 2015)
- In offshore solutions the high wave energy resources will expose the WECs to great forces, making the WEC robustness an important issue. Wind power on the other hand is a mature technology and the already available turbines are very robust. In addition, the high sea states will limit the access for operations and

maintenance. (Dalton et al. 2010, O'Connor et al. 2013a, Lopez et al. 2013, Farrell et al. 2015)

- No full-scale wave farms exist to date. Therefore the environmental impacts are not yet clear. If problems would arise, it could stop the development of wave power. (Langhamer et al. 2010)
- Power output of the current WECs is neither at the needed level nor it is clear how big the usable market area would be for wave power. Also the power output fluctuation is problematic. Below in table 4 are listed the main factors affecting WEC output variability according to Farrell et al. (2015) literature review.

Table 4. A review of factors effecting WEC output fluctuation (Farrell et al. 2015).

Factor	Effect	Source
WEC design	0,08 (Aquabuoy) - 0,26 (Pelamis)	Dunnett & Wallace 2009
	0,29 (Pelamis) - 0,32 (Wavestar)	O'Connor et al. 2013a
	0,41 (Wavestar) - 0,54 (Pelamis)	O'Connor et al. 2013b
Location	0,16 - 0,26 (Canada)	Dunnett & Wallace 2009
	0,29 (Ireland) - 0,54 (Spain)	O'Connor et al. 2013a
Climate variability	0,68 (min) - 0,92 (max)	Guanche et al. 2014
Variability of output availability	0,49 (Early Reliability) - 0,75 (Mature Reliability)	O'Connor et al. 2013a

On the other hand, wave power has numerous benefits compared to other competing or existing technologies. Below are listed these benefits that can bring advantage if the main issues are solved.

- Waves can travel long distances with little energy loss. For example the storms originated in western side of the Atlantic Ocean will travel to the western coast of Europe with little energy loss (Lopez et al. 2013).
- Wave power is greater in amount and more reliable than for example wind power. When wave power's density is about 2 - 3 kW/m^2, wind power is between 0.4 – 0.6 kW/m^2 and solar power's value is between 0.1 - 0.2 kW/m^2 (Lopez et al. 2013).
- Wave energy converters can generate power up to 90 % of the time (Lopez et al. 2015) when the same percentage is between 20 and 30 % for wind and solar devices **(**International Energy Agency 2013).
- Its predictive capacity is far greater than wind energy's (Lopez et al. 2013).
- Wave energy has a good correlation between resource and demand, since around 37% of the population of the world lives within 90 km of the coast (Lopez et al. 2013). On the other hand, Ferrell et al. (2015) list this as a risk due to a small percentage.

- It is a widely available energy source because it has multiple locations (from shoreline to deep waters) (Personal communication with Wello Oy and AW-Energy presentatives).
- It has (according to current knowledge) little environmental interference and in addition it can decrease the seabed erosion by muffling the wave's energy (Lopez et al. 2013). Langhamer et al. (2010) state that since no full size wave parks are existing, reliable environmental impact analysis' is still impossible to make.

Wave power has many benefits over other methods of energy production and so it has disadvantages and problems that need to be solved. An important factor for any energy production method is the available resource and the market size, which are taken into consideration in the following chapter.

3.3. Global wave energy resources

Below, in figure 3, are presented annual average wave energy resources in the world. As can be seen the most energy intensive areas are between 60° and 40° latitudes on both hemispheres and the intensity is gradually decreasing when moving towards the Equator and the poles (Cornett 2008, Lopez et al. 2013, Astariz & Iglesias 2015). However, when Northern and Southern Hemispheres are compared, it can be seen that the Southern Hemisphere is more energy intensive. In the Southern Hemisphere the highest energy resources are in the South-Indian Ocean, south and southwest from Australia and southern Pacific. In these areas the annual energy can reach values over 120 kW/m and in some areas even over 200 kW/m. These high-energy areas are mainly too far from the coast and too deep to be reasonably exploited (Cornett 2008). In addition, in areas over 120 kW/m the storm conditions are too demanding for the current concepts (Lopez et al. 2013). On the other hand both the seasonal and temporal variety is lower in the Southern Hemisphere making the energy production possibilities more stable (Cornett 2008). Sites with steadier resources are more viable than the ones with more variation in energy. The current WEC designs are optimized for certain wave conditions and therefore cannot adapt to the changing energy levels in real time. Hence steadier energy resource will help the wave converters to work more efficiently at all times. The highest accessible energy levels in the Southern Hemisphere are found in southern Chile, South Africa and south - and west coast of Australia and New Zealand. (Cornett 2008, Lopez et al. 2013)

Regarding the Northern Hemisphere, the highest values are found in the North Atlantic zone, on the west coast of the British Isles, Iceland and Greenland, where the water depth is reasonable 50 - 60 m (Cornett 2008). Energy values in these areas are between 90 and 80 kW/m and decreasing when moving towards the Continental Europe. Figure 4 shows the estimated accessible power densities in Europe. As can be seen from fig. 4: in Portugal, France and northern Spain the wave conditions are still reasonably good, with power density values ranging between 30 and 55 kW/m.

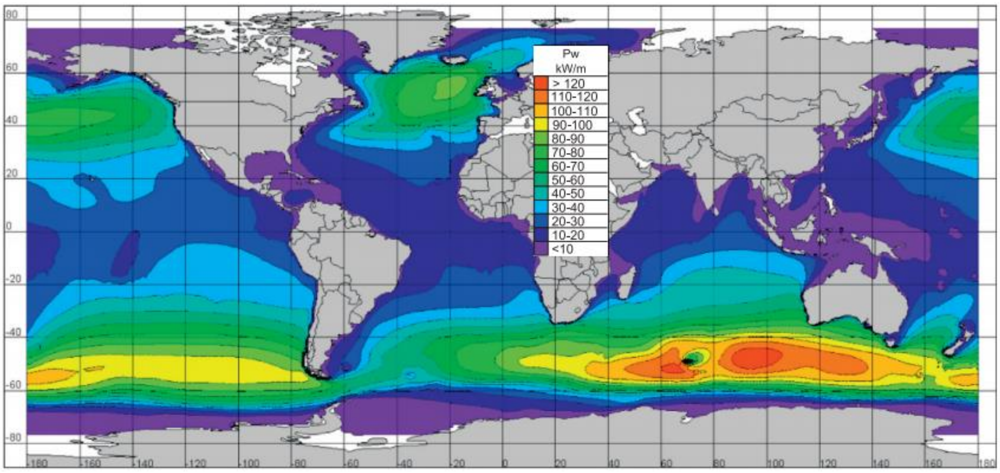

Figure 3. Global annual wave power estimation (Cornett 2008).

Table 5 displays the theoretical power values (in GW) for different market areas in the world. The P_{gross} presents the absolute power in the location's sea area. P is P_{gross} without areas averaging less than 5 kW/m and finally P_{net} excludes ice covered areas and areas with average resource under 5 kW/m. The table (5) shows that Australia and New Zealand have the greatest resource, followed by North -and West Europe with cumulative net power of 286 GW. An advantage for the European market is that the population density is higher than in western Australia. In eastern Australia, where the population density is highest, the wave resource is considerably smaller.

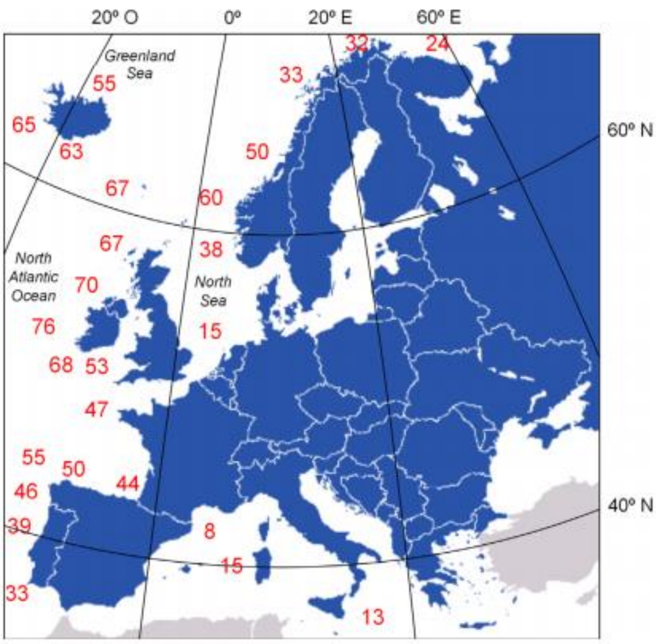

Figure 4. European distribution of annual wave power in kW/m (Lopez et al. 2013).

Due to its high resource and dense population, Europe offers the most potential market in the world. In addition it has to be taken into account that wave power need to be subsidized for an extensive period of time before it can truly be competitive. Unlike Europe, most market areas won't be able to, or are not willing to, provide high subsidies in the early stages of development.

Table 5. Global theoretical wave power resource (Mørk et al. 2010).

Resource	P_{gross} [GW]	P [GW]	P_{net} [GW]
Europe (N and W)	381	371	286
Baltic Sea	15	4	1
European Russia	37	22	3
Mediterranean	75	37	37
North Atlantic Archipelagos	111	111	111
North America (E)	115	103	35
North America (W)	273	265	207
Greenland	103	99	3
Central America	180	171	171
South America (E)	206	203	202
South America (W)	325	324	324
North Africa	40	40	40
West and Middle Africa	77	77	77
Africa (S)	178	178	178
Africa (E)	133	133	127
Asia (E)	173	164	157
Asia (SE) and Melanesia	356	283	283
Asia (W and S)	100	90	84
Asiatic Russia	172	162	23
Australia and New Zealand	590	574	574
Polynesia	63	63	63
Total (GW)	3703	3474	2986

In table 6 are listed estimations of total exploitable wave power resources (in GW) for some European countries that have been active in the wave power development. According to the listing UK leads with its 120 GW, followed by France with 28 GW. Other countries with notable resources are Ireland and Portugal with 21 GW and 10 GW respectively.

Table 6. Accessible wave power levels in Europe (Lopez et al. 2013).

Country	P_{net} [GW]
UK	120
Sweden	1
France (Gulf of Gascoigne)	28
Ireland	21
Portugal	10
Denmark	3,4

3.4. Locational energy data and annual output of Wello Penguin

Tables and figures in chapters 3.3 give an understanding of the existing global wave energy resource and therefore the market potential. Still due to the WEC specifications, wave energy converters cannot utilize all of the power that waves carry. The power capture efficiency and cut in wave height limit (CIWHL) limit the actual power production possibilities. Additionally, in high sea states, none of the power exceeding the WEC's maximal momentary output level can be utilized. To get a better understanding of waves' potential as a power source, five locations with published scatter plots have been selected for more detailed analysis. Figure 5 shows the selected locations for the analysis on a map.

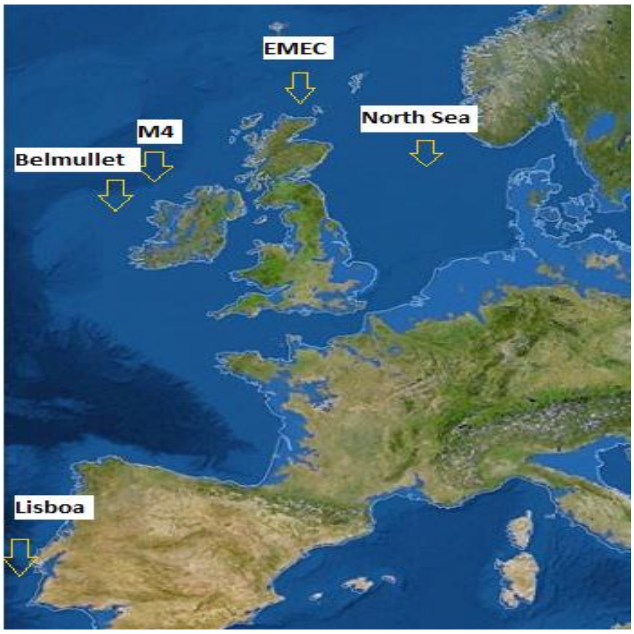

Figure 5. Selected wave buoy locations.

As it was stated: Europe presents the most potential market for wave power and therefore all five locations selected are from West -and North Europe. The selected locations are Belmullet and M4 test sites in Ireland, EMEC in Scotland, North Sea site between southern Norway and Scotland and the last site is outside Lisboa. The assumption at this point is that: at least medium (>20 W/m) wave resource is needed for any kind of commercial wave energy applications. Therefore the selected sites are high or medium resource, offshore -and deep-water locations with power ratings ranging from 20 to 70 kW/m. This and other resource needs will be discussed later with the feasibility calculations. The M4 site is located approximately 9 km off the Irish coast and the water depth is approximately 50 m (Dalton et al. 2012). The observation period for M4 could not be found. The Belmullet site is approx. 44 km from the coast of Mayo, in a water depth of 72 m. The observation period for the wave data is from 1987 to 1994. (Dalton et al. 2012) The EMEC test site is located on the west coast of the Scottish Orkney islands, approx. 2 km from the shore at a depth of 50 meters (Nielsen & Pontes 2010). Observation period for the EMEC site was not stated. For Lisboa test site no specific distance to the shore could be found, but coordinates 54° N, 12° W are said to present the site's location. These coordinates would locate the site about hundred kilometers east of the coast of Portugal. Observation for Lisboa wave data is between 1987 and 1994. The North Sea data is from an observation buoy located in coordinates 56,23° N, 2,03° E and hence placing it between southern Norway and Scotland, about 200 km east from the Scottish coast. The observation period for the North Sea data was 1984 - 1994. The scatterplot data from the selected sites are presented in tables 7 - 11. All scatter plots are presented with wave height (m) and wave energy period T_e. The energy period conversions are performed by using equations 2 and 3.

Table 7. Scatter plot hours for M4 buoy (Dalton et al. 2012).

		Te (s)													
		1,2	2,4	3,6	4,8	6	7,2	8,4	9,6	10,8	12	13,2	14,4	15,6	16,8
Hs (m)	0,5				52	130	25								
	1		8	41	164	387	151	59	11						
	1,5		5	44	82	488	360	236	75	12					
	2			26	65	293	503	258	142	31	4				
	2,5				76	107	354	386	139	26	5	3	1		
	3				30	45	226	496	201	41	1	2			
	3,5				1	26	44	352	227	82	9				
	4					23	19	181	252	99	19	3	1		
	4,5					9	9	71	210	99	19	4			
	5					2	6	6	158	123	30	3	1		
	5,5							3	81	144	29	10	3		1
	6							4	21	100	44	7	4		1
	6,5							4	6	47	42	11	4		
	7							4		27	57	16	3		
	7,5								3	14	33	19			
	8									3	29	21	5		
	8,5									1	21	17	2		
	9										4	15	2	2	
	9,5										1	9	1		
	10											2	3	1	
	10,5											2	1		
	11												2		
	11,5													1	
	12														
	12,5													1	

Table 8. Scatter plot hours for Belmullet (Nielsen & Pontes 2010).

		Te (s)												
		<3	3,5	4,5	5,5	6,5	7,5	8,5	9,5	10,5	11,5	12,5	13,5	14,5
Hs (m)	0,25													
	0,75				8,8	44,0	52,8	8,8						
	1,25				70,4	246,3	387,0	202,3	61,6					
	1,75				70,4	334,2	422,2	395,8	211,1	44,0				
	2,25				8,8	246,3	325,4	263,9	290,2	123,1	26,4			
	2,75					61,6	299,0	263,9	219,9	158,3	52,8	8,8		
	3,25					8,8	140,7	246,3	175,9	158,3	79,2	8,8		
	3,75						35,2	184,7	149,5	131,9	105,5	44,0	8,8	
	4,25						8,8	123,1	167,1	123,1	88,0	44,0	17,6	
	4,75							35,2	131,9	123,1	88,0	44,0	26,4	
	5,25							8,8	79,2	114,3	79,2	35,2	17,6	8,8
	5,75								26,4	96,7	79,2	44,0	17,6	8,8
	6,25								17,6	61,6	52,8	44,0	17,6	8,8
	6,75									35,2	44,0	35,2	17,6	8,8
	7,25									17,6	35,2	26,4	17,6	8,8
	7,75									8,8	26,4	35,2	17,6	8,8
	8,25										17,6	17,6	17,6	8,8
	8,75										8,8	17,6	17,6	8,8
	9,25											8,8	8,8	
	9,75											8,8	8,8	8,8
	10,25	g											17,6	8,8
	10,75	p												8,8
	11,25													

Table 9. Scatter plot hours for Lisboa (Nielsen & Pontes 2010).

	Te (m)														
		<3	3,5	4,5	5,5	6,5	7,5	8,5	9,5	10,5	11,5	12,5	13,5	14,5	15,5
Hs (m)	0,5				4,6	27,5	32,0	4,6	4,6						
	1				45,8	201,4	320,4	59,5	59,5	4,6					
	1,5				73,2	379,9	498,9	219,7	219,7	109,8	27,5	4,6			
	2				36,6	338,7	375,3	306,6	306,6	238,0	146,5	27,5	4,6		
	2,5				4,6	164,8	297,5	247,1	247,1	228,8	247,1	96,1	22,9		
	3					32,0	201,4	178,5	178,5	164,8	196,8	137,3	45,8	4,6	
	3,5						77,8	128,2	128,2	123,6	100,7	100,7	59,5	13,7	
	4						13,7	96,1	96,1	82,4	54,9	64,1	50,3	22,9	4,6
	4,5						4,6	64,1	64,1	45,8	50,3	45,8	32,0	27,5	9,2
	5							32,0	32,0	36,6	36,6	27,5	22,9	18,3	9,2
	5,5							13,7	13,7	27,5	18,3	13,7	13,7	9,2	4,6
	6							4,6	4,6	18,3	13,7	9,2	4,6	4,6	
	6,5									9,2	9,2	9,2			
	7										4,6	4,6			
	7,5														
	8														
	8,5														
	9														
	9,5														

Table 10. Scatter plot hours for North Sea (Nielsen & Pontes 2010).

	Te (s)											
		<3	3,5	4,5	5,5	6,5	7,5	8,5	9,5	10,5	11,5	12,5
Hs (m)	0,25		35,2	123,1	61,6	35,2	17,6					
	0,75		79,2	562,9	492,5	202,3	88,0	52,8	17,6	8,8		
	1,25			334,2	818,0	360,6	131,9	61,6	17,6	8,8		
	1,75			17,6	659,6	562,9	184,7	79,2	35,2	8,8		
	2,25				202,3	668,4	219,9	70,4	35,2	8,8		
	2,75				17,6	431,0	281,4	88,0	35,2	8,8	8,8	
	3,25					167,1	334,2	79,2	26,4	8,8		
	3,75					26,4	237,5	105,5	17,6	8,8		
	4,25						114,3	105,5	17,6			
	4,75						26,4	96,7	17,6	8,8		
	5,25						8,8	70,4	26,4			
	5,75							26,4	26,4	8,8		
	6,25							8,8	17,6	8,8		
	6,75								8,8	8,8		
	7,25								8,8			
	7,75											

Table 11. Scatter plot hours for EMEC (Nielsen & Pontes 2010).

	Te (s)														
		<3	3,5	4,5	5,5	6,5	7,5	8,5	9,5	10,5	11,5	12,5	13,5	14,5	15,5
Hs (m)	0,25		240,1	327,4	175,8	71,6	32,2	22,6	12,4	2,8	0,2				
	0,75		205,7	847,3	524,3	186,7	66,4	16,5	7,7	3,6	0,2				
	1,25		41,0	586,7	631,4	266,6	102,3	29,7	9,6	3,4	0,0	0,8	0,6	0,2	
	1,75		11,8	184,1	692,4	183,1	93,1	31,9	12,6	1,9	0,0	0,0	0,5	0,0	
	2,25			26,1	489,1	347,3	97,8	28,9	16,7	6,0	0,8	0,0	0,0	0,0	
	2,75			2,4	102,7	459,0	102,7	21,2	12,4	4,7	1,5	0,2	0,0	0,2	
	3,25			0,5	12,4	296,6	181,2	22,6	9,6	3,2	1,7	0,6	0,0	0,0	
	3,75				1,3	5,2	245,6	37,6	8,3	1,3	0,8	0,2	0,0	0,0	
	4,25					0,6	156,1	49,8	8,5	3,6	1,7	0,0	0,5	0,5	
	4,75					0,0	38,9	77,9	10,7	2,4	1,3	0,5			
	5,25					0,0	4,1	69,4	13,0	2,8	0,5	0,0			
	5,75					0,2	0,0	24,2	23,1	0,6	0,2	0,5			
	6,25						0,5	4,9	20,5	1,3	0,5	0,0			
	6,75						0,5	0,5	12,8	7,2	0,5	0,0			
	7,25								6,0	10,0	0,0	0,2			
	7,75								2,8	9,9	0,2	0,2			
	8,25								0,6	2,8	1,9	0,0			
	8,75									2,4	2,4	0,0			
	9,25									0,2	1,7	0,5			
	9,75										1,3	0,2			
	10,25										0,6	0,2			
	10,75											0,2			
	11,25											0,5			
	11,75														

In order to estimate the actual output of a wave energy converter on any location a power matrix of the capture information is needed. According to Wello presentatives, a rough estimation can be used, that the Penguin WEC can convert about 20 % of the wave's energy into electricity. Notable here is, that the 20 % capture ratio is for the active width of the hull, excluding the drift. The converter's movement in the sea, during one cycle, is considerably smaller than the drift value of 25 m. Therefore the drift value is not considered in the power production estimations. The active width of the existing device is 18 m and the next generation device will be 23.4 m. The cut in wave height (CIWH) for power production is 1 - 1.5 meters. (Personal communication with Wello presentative) According to Wello Oy, the machine does not have an upper wave height limit for electricity production since the vessel should be able to float through the oversized waves and therefore produce electricity in all (high) wave conditions (Personal communication with Wello presentative). Power output matrix for the Wello Penguin is presented in table 12 and a more detailed description of the Penguin WEC can be found in chapter 4**.**

Table 12. Power matrix model for Wello Penguin (kW).

	Te (s)														
		1,2	2,4	3,6	4,8	6	7,2	8,4	9,6	10,8	12	13,2	14,4	15,6	16,8
Hs (m)	0,5														
	1	1,3	2,7	4,0	5,3	6,6	8,0	9,3	10,6	12,0	13,3	14,6	16,0	17,3	18,6
	1,5	6,0	12,0	17,9	23,9	29,9	35,9	41,9	47,9	53,8	59,8	65,8	71,8	77,8	83,7
	2	10,6	21,3	31,9	42,5	53,2	63,8	74,4	85,1	95,7	106,3	117,0	127,6	138,2	148,9
	2,5	16,6	33,2	49,8	66,5	83,1	99,7	116,3	132,9	149,5	166,1	182,8	199,4	216,0	232,6
	3	23,9	47,9	71,8	95,7	119,6	143,6	167,5	191,4	215,3	239,3	263,2	287,1	311,0	335,0
	3,5	32,6	65,1	97,7	130,3	162,8	195,4	228,0	260,5	293,1	325,7	358,2	390,8	423,3	455,9
	4	42,5	85,1	127,6	170,1	212,7	255,2	297,7	340,3	382,8	425,3	467,9	510,4	552,9	595,5
	4,5	53,8	107,7	161,5	215,3	269,2	323,0	376,8	430,7	484,5	538,3	592,2	646,0	699,8	753,7
	5	66,5	132,9	199,4	265,8	332,3	398,8	465,2	531,7	598,1	664,6	731,1	797,5	864,0	930,4
	5,5	80,4	160,8	241,2	321,7	402,1	482,5	562,9	643,3	723,7	804,2	884,6	965,0	1045,4	1125,8
	6	95,7	191,4	287,1	382,8	478,5	574,2	669,9	765,6	861,3	957,0	1052,7	1148,4	1244,1	1339,8
	6,5	112,3	224,6	337,0	449,3	561,6	673,9	786,2	898,5	1010,9	1123,2	1235,5	1347,8	1460,1	1500,0
	7	130,3	260,5	390,8	521,0	651,3	781,6	911,8	1042,1	1172,4	1302,6	1432,9	1500,0	1500,0	1500,0
	7,5	149,5	299,1	448,6	598,1	747,7	897,2	1046,7	1196,3	1345,8	1495,3	1500,0	1500,0	1500,0	1500,0
	8	170,1	340,3	510,4	680,5	850,7	1020,8	1191,0	1361,1	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0
	8,5	192,1	384,1	576,2	768,3	960,3	1152,4	1344,5	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0
	9	215,3	430,7	646,0	861,3	1076,7	1292,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0
	9,5	239,9	479,8	719,8	959,7	1199,6	1439,5	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0
	10	265,8	531,7	797,5	1063,4	1329,2	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0
	11	293,1	586,2	879,3	1172,4	1465,4	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0
	11	321,7	643,3	965,0	1286,7	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0
	12	351,6	703,1	1054,7	1406,3	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0
	12	382,8	765,6	1148,4	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0
	13	415,4	830,7	1246,1	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0

The power matrix model has been made with equation 1 and with the stated energy capture ratio of 20 %. In the power matrix the CIWHL is 1 m. An important factor is that the WEC would not be able to produce energy in the most extreme wave height and energy period time combinations (upper right -and lower left corners of table 12). An assumption can be made that the possible wave conditions are in the limits of the WEC's capabilities to produce electricity. Therefore the power matrix shows power values in all possible conditions even though the most extreme combinations are not possible (Babarit et al. 2012). In the power matrix a maximum momentary electricity production power is set to 1500 kW. The 1500 kW maximum power is an assumption based on the information that momentary production level can exceed the 1 MW power rating of the WEC (Personal communication with Wello presentative).

The locational electricity output data, acquired with the scatter plot –and the power matrix information, is presented in tables 13 and 14. Firstly, the average maximum available energies (MWh/m) have been calculated by using equation 1. From these result the average locational power levels (kW/m) has been calculated by dividing the annual energy by the stated hours measured. Next the annual electricity output levels have been calculated with 100 % availability by multiplying the scatter plot hours of the locations with the modelled Penguin power matrixes. The energies have been calculated with both 1 and 1.5 m cut in wave height limits. From table 13 can be seen, that the cut in wave height limit does not create a great difference for the overall production, especially in the high resource areas. In M4 and Belmullet the modelled energy output gain is only 1.3 and 0.5 % respectively, when changing the CIWHL from 1 m to 1.5 m with the 20 % energy capture efficiency. In Lisboa the gain was 2.3 %. In the sites with lesser resources, the difference was greater: 4.6 % in EMEC and 4.4 % in the North Sea site. This is due to the fact that at the high resource sites the average wave height is higher.

Table 13. Comparison of different sites.

Power of location [kW/m]			
North Sea	19,9		
M4	53,9		
Lisboa	38,9		
Belmullet	69,5		
EMEC	20,9		
Max Energy [MWh] 1 m CIWHL			
Power Capture ratio	20 %	25 %	30 %
North Sea	803,2	1 004,0	1 202,2
M4	2 103,9	2 539,8	2 938,6
Lisboa	1 575,2	1 957,5	2 326,4
Belmullet	2 612,9	3 118,3	3 572,3
EMEC	827,5	1 018,6	1 203,3
Max Energy [MWh] 1,5 m CIWHL			
North Sea	768,2	960,2	1149,7
M4	2076,2	2505,2	2897,0
Lisboa	1538,9	1912,2	2272,0
Belmullet	2600,9	3103,4	3554,4
EMEC	789,4	971,0	1146,3

In table 13 there are two extra columns for capture ratios of 25 and 30 %. These are the maximum annual energy outputs for the same Wello Penguin 1 MW WEC, with maximum momentary power output level of 1500 kW and active width of 23.4 m but with power capture ratios of 25 and 30 %. Since the Penguin is still far from being a mature product it is excepted that the power capture of the WEC will increase throughout the development. One of the main development goals of Wello is to increase the capture efficiency (Personal communication with Wello presentative). Therefore the 25 and 30 % capture values are showing the future potential of annual energy outputs. Power matrixes for the 25 and 30 % capture efficiencies are presented in appendix 2. When moving from the power capture ratio of 20 to 25 %, the increase in the annual energy produced for North Sea, Lisboa and EMEC is 25.0, 24.2 and 23.1 % respectively and for the higher resource sites M4 and Belmullet the increase is 20.7 % and 19.3 %. Moving from 20 to 30 % energy capture ratios, the energy changes are 49.7, 47.7 and 45.4 % for North Sea, Lisboa and EMEC and 39.7 and 36.8 % for M4 and Belmullet. The increases are smaller for the high resource locations, since the maximum momentary power of 1500 kW is reached more often.

The "storm percentage" values are also calculated from the scatter plot hours. The storm percentage is the time (percentage) when the converter is not accessible for maintenance. The storm percentage has been calculated with an access wave height limit of 2 meters (The maintenance plan is presented with more detail in chapter 4). The presented numbers are somewhat optimistic, since the time period is not always long enough for operations and maintenance (O&M) actions, but in absence of more specific data this fact is ignored. The storm percentage values are presented in table 14. The only surprise in the storm percentage values is the order between North Sea and EMEC: EMEC has a greater resource, but the storm percentage value is smaller than the corresponding value of North Sea. Other than that exception the storm percentage increases accordingly with the energy resources.

Table 14. Storm Percentages for 2 m wave limit of different locations.

Location	Storm percentage
M4	65,88 %
Belmullet	70,78 %
Lisboa	63,32 %
North Sea	42,27 %
EMEC	36,68 %

The storm percentage is an important number when estimating the availability levels of wave power technologies. Combining the storm percentage values (accessibility) and equation 4, the availability values for certain technologies can be drawn. In figure 6 are presented the availability estimations with three different accessibility levels, as described in chapter 2.2. The benchmark for these estimations is based on wind power. The chosen maximum availability levels are 99 % for mature and robust technologies and 98 and 97 % for more immature technologies (Van Bussel 2009). From table 14 and figure 6 can be seen that the storm percentages range between 36.68 % and 70.78 %, making the availability levels change between 41 - 76 %, with max availability of 97 %. The availability values range between 68 - 87 %, with max availability of 98 % and with the mature max availability (99 %) the range is between 91 and 97 %. This gives an indication that the reliability of the WEC is an important factor for the energy production and therefore for the feasibility.

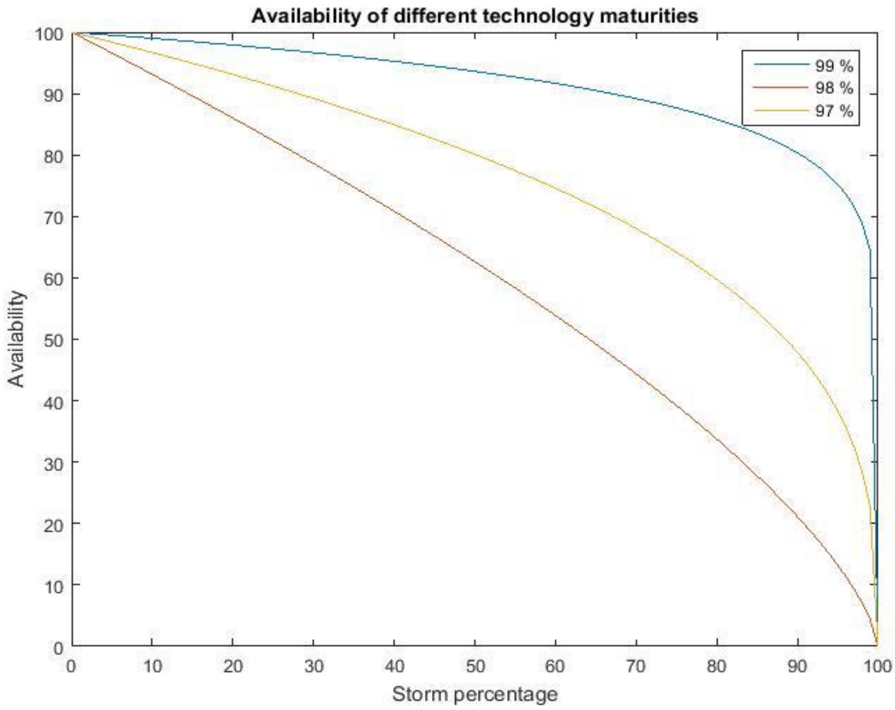

Figure 6. Availability of a WEC converter.

In table 15 are presented the calculated annual output levels of the Penguin WEC in different locations. The estimations are presented with both 1 and 1.5 m cut in wave height limits and with maximum availability (Maxavail.) levels of 97, 87.5, 98 and 99 %. The used maximum annual energy is based on the current 20 % capture efficiency. In Belmullet, which is the most energy rich location, the effect of the reliability can be more than 100 % of the annual production. Table 15 shows that similar effects are seen also in the other locations.

Table 15. Annual electricity production with different availabilities with 20 % power capture rate (MWh).

Max availability level	97 %	97,50 %	98 %	99 %
CIWHL 1 M				
North sea	554,3	616,6	673,7	762,4
M4	1 018,20	1 254,00	1 491,40	1 899,60
Lisboa	800,4	972,1	1 142,70	1 432,00
Belmullet	1 138,70	1 445,30	1 762,50	2 324,60
EMEC	607,8	664,1	714,9	792,3
CIWHL 1,5 M				
North sea	530,2	589,7	644,3	729,1
M4	1 004,70	1 237,50	1 471,80	1 874,60
Lisboa	781,9	949,7	1 116,40	1 399,00
Belmullet	1 133,50	1 438,70	1 754,40	2 314,00
EMEC	579,9	633,6	682	755,9

In this chapter the energy resource, the possible annual output values and the future tariffs have been estimated. In the next chapter the last needed starting values for the feasibility, the costs, are estimated.

4. COST STRUCTURE OF WELLO PENGUIN WAVE ENERGY CONVERTER

The main reference concept in this thesis is the Penguin WEC, developed by a Finnish company Wello Oy. Wello's patented key invention is to convert the wave's movement into gyration. The vessel uses the hull's asymmetric shape to capture the wave's energy to a spinning rotator inside the hull. Power is then directly led from the rotator to the generator by using the same shaft. The Penguin is an offshore wave energy converter designed for high energy resource sites. Figure 7 shows the Penguin on a site in Scotland and the structure of the WEC is shown in figure 8 (wello.eu). Wello's technology is unique in the sense that it converts the periodical wave energy directly into electricity with continuous rotational movement, in comparison to back and forth movement with discontinuity. The motion is converted to electricity without any moving joints or gears and all parts are sealed inside the floating iron hull to increase its robustness. Wello is using components familiar in wind turbines which is made possible due to the similar spinning motion of the two technologies. (wello.eu) In figure 8 the rotor is colored with red and the generator above is yellow. As can be seen, the rotor and the generator are connected with same shaft (presented with light grey in fig**.** 8).

Figure 7. Penguin in a site (wello.eu).

The investors of Wello Oy are VNT Management Oy and Finnvera. In addition TEKES has invested in the company. In 2014 Fortum bought a minority share of the company and now possesses 13.6 % of Wello Oy. (wello.eu) In June 2015 Wello has announced that the European Commission's research and innovation programme Horizon 2020 has granted a 17 M€ founding for the Clean Energy From Ocean Waves (CEFOW) research project that is coordinated by Fortum. The mission of the project is to research and develop the use of the Penguin WEC in electricity grid connected ocean conditions. This programme will lead into a multi device test site at Cornwall, Great Britain, where Fortum has leased a sea area.

The other relevant wave energy converter is Pelamis P1. The P1 is widely used in research, since it is the only wave energy converter that has released a specific power matrix. The Pelamis P1 does not provide a good research subject in 2015, since the wave energy conversion technology was proven uneconomical and the company suffered bankruptcy in 2014 (Breaking Energy 2014). The Pelamis P1 is used as a benchmark for the Wello Penguin since they have many similarities in preferred location, in optimal wave conditions and in needed external components. Short description of the Pelamis P1 can be seen in appendix 1**.**

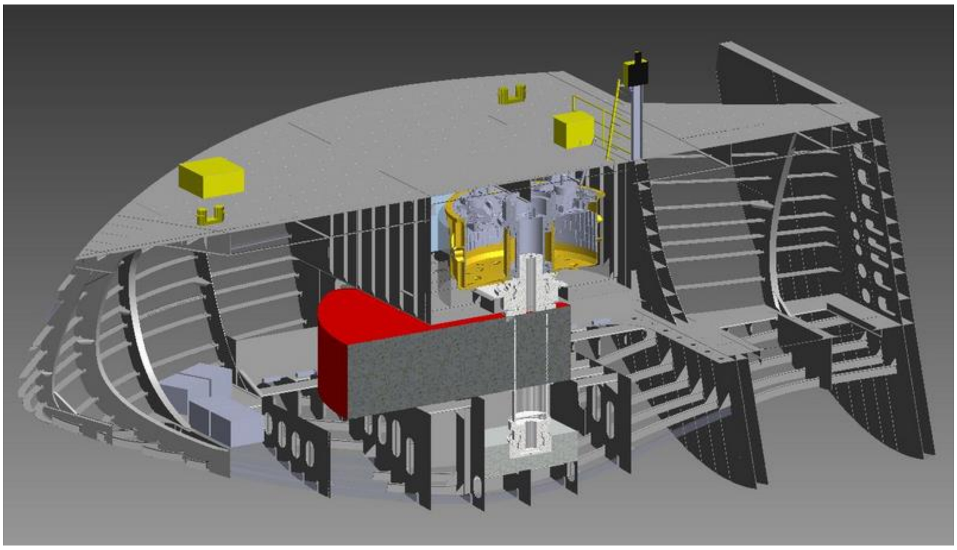

Figure 8. Penguin concept (wello.eu).

According to Astariz & Iglesias (2015) categorization the main cost components of a wave energy plant are:

1. Pre-operating costs (+ licenses and permissions and GHG investigations)
2. Capital expenditures (CAPEX)
3. Operational expenditure (OPEX)
4. Decommissioning costs.

Term initial costs (IC) will be used from now on to include pre-operating costs and the capital expenditures. A closer look is taken into the costs following this categorization starting with the pre operating costs.

4.1. Pre operating

The pre-operating costs include the cost of preliminary studies, projects, environmental impact assessment, consenting procedures etc., in addition to coordination costs (Astariz & Iglesias 2015). These expenditures are often described as 10 % of initial costs (excluding greenhouse gas (GHG) investigations and licenses and permissions) (Previsic 2004;

Dalton et al. 2010; Astariz & Iglesias 2015) or between 500 000 and 2 000 000 €/MW (Astariz & Iglesias 2015). The part of the costs associated with procedures for licenses and permissions is about 2 % of the initial cost of the WEC (Dalton et al. 2010, Dalton et al. 2012, Astariz & Iglesias 2015) or more specifically 2.8 % of the power value of the WEC (Dalton et al. 2010, Dalton et al. 2012). For example in a case of a 100 MW installation the cost would be 2.8 M€. Dalton et al. (2010 and 2012) state that greenhouse gas investigations (GHG) cause costs that are 0.05 - 2 % of the WEC initial costs (WECIC) and that 1 % is a good starting estimate. Pre operating costs should be similar to different concepts since the same steps need to be taken for all devices. Below in table 16 is a summary of the pre-operating costs. All of these mentioned estimations are acquired by benchmarking early stage offshore wind parks.

Table 16. Pre-operating and licenses costs.

Category	Cost	Source[a]
Pre-Operating costs	10 % CAPEX (€)	A, C, D
	500 000 - 2 000 000 €/MW	A
Licenses and permissions	0,028 (M€) x Installed Power (MW)	A
	2 % IC of WEC	A, B, C
GHG Investigations	2 - 0,05 % IC of WEC	B, C

[a]A: Astariz & Iglesias 2015, B: Dalton et al. 2012, C: Dalton et al. 2010, D: Previsic 2004

4.2. Capital Expenditures

Capital Expenditures (CAPEX) include the following components that need to be taken into consideration (Dalton et al. 2012):

- WEC
- Mooring
- Cable/pipeline
- Substations/converters
- Installations (e.g. of device, moorings, cables, or electrical connections),

and these cost components of CAPEX can be calculated

$$CAPEX = N \text{ x } C_{WEC} + L_{offshore} \text{ x } C_{und.cab} + L_{onshore} . C_{subt.cab} + C_{subest} + C_{mooring},$$

where N is the number of converters, C_{WEC} is the cost of one converter and its installation, $L_{offshore}$ is the length of the underwater electric cable, $C_{und.cab}$ is the cost per unit length of underwater cable (+ installation), $L_{onshore}$ is the length of the underground cable up to the existing electrical network, $C_{subt.cab}$ is the cost per unit length of underground cable and its installations, $C_{subest.}$ is the substation cost with installations and $C_{mooring}$ is the cost of the mooring system and its installation (Dalton et al. 2012, Astariz & Iglesias 2015).

4.2.1. WEC

The current version of the Penguin, which is now in full-scale test use in Scotland, is a one megawatt converter weighing 300 - 250 tons (iron). The current WEC has an active width of 18 m and the next generation converters will be 23.4 m. The basic WEC information is presented in table 17. The manufacturing of the hull can be done by most commercial shipyards. Installation can also be done by local commercial ships by towing the WEC into location and therefore no cranes or special machinery is needed. (wello.eu)

Table 17. Wello Penguin specs.

Wello 1 MW converter	
Weight (tons)	250 - 300
Cost (M€)	250 - 300
Width (m)	18 - 23,4
Drift (m)	25

The developer of the Penguin converter has provided a rough estimate of the WEC cost, which lies between 2.5 and 3 M€ (Personal communication with Wello presentative) The WEC price comprises the purchase of the device and the costs of installation. For comparison, Dalton et al. (2010)**,** Dalton et al. (2012) and Astariz & Iglesias (2015) have estimated the cost of the Pelamis P1 to range between 2.1 and 6 M€/MW. The WEC cost estimations are presented below in table 18.

Table 18. WEC prices.

WEC DEVICE	M€/MW[b]	Source[a]
Penguin	2,5 - 3	A
Pelamis P1	2,1 - 6	B, C, D,

[a]A: Personal Communication with company representative B: Dalton et al. 2012, C: Dalton et al. 2010, D: Astariz & Iglesias 2015

[b]Prices are adjusted with European scrap metal prices

4.2.2. Mooring

An important part of the wave energy system is the mooring. A number of studies that have estimated the mooring costs for the Pelamis P1 use an estimation of 10 % of the WEC's initial cost for the mooring hardware (Dalton et al. 2010, Dalton et al. 2012, Allan et al. 2013, O'Connor et al. 2013a, Astariz & Iglesias 2015). When the Pelamis P1 and the Wello Penguin are compared, exactly the same components and methods can be used, since both of them are floating offshore -and high energy resource wave energy converters.

In addition to the hardware costs of the mooring, the installations causes costs. The installation costs are caused mainly by the rent of the mooring vessel and by the installation crew salaries. The costs of the mooring vessel is about 50 000€/day according to Lorenzo et al. (2010), and the mooring takes between one and two days (Lorenzo et al. 2010). Farrell et al. (2015) write that the mooring of one floating Pelamis P1 device takes 6 days with a daily cost of 5 871 €. Farrell et al. (2015) write that these cost estimations are acquired from provider surveys. The mooring cost estimations are presented in table 19**.**

Table 19. Mooring costs.

Moorin	Cost	Source
Hardware	10 % of WECIC	A, B, C, D, E
Installation	50 000 €/Day	F
	1 - 2 days	F
	5871 €/Day	G
	6 Days/WEC	G

[a]A: Dalton et al. 2010, B: Dalton et al. 2012, C: Allan et al. 2013, D: O'Connor et al. 2013a, E: Astariz & Iglesias, F: Lorenzo et al. 2010, G: Farrell et al. 2015

Another cost that need to be taken into account comes from mooring cable changes. Due to the constant movement of the converter, the anchoring cables are exposed to metal fatigue. Therefore the mooring cables need to be changed estimated every seven years (personal communication with Wello presentative). This means that one or two anchoring cable changes are needed depending on the calculated lifetime of the wave energy converter. An accurate estimation of the mooring cable changing costs is not available and therefore an assumption is made that all of the hardware, such as the bottom attached anchors, do not need to be changes. An estimation is made, that the mooring change cost is 80 % of the original cost corrected with inflation.

4.2.3. Cables and electrical installation

Apart from the WEC and mooring costs, the wiring and electrical installations are the key elements of wave farms. The amount of the cable needed depends on the distance to the shore. In systems of multiple WECs (in wave parks), the different converters can be connected to same cables. In this situation the layout of the park determines the cable requirements. The WECs are typically grouped and connected in series and then attached to a hub. The optimal distances between the WECs depend on the type and number of the WECs and on the locational wave climate (Astariz & Iglesias 2015). If the WECs are too close to each other, they can effect negatively on each other's performance. When the distances are being grown, the negative effects can be deleted, but that increases the cable need. Some studies suggest a spacing of 100 m (Brekken et al. 2012). Other suggest values related to the WEC diameter, with a typical value of 10 times the device diameter (Astariz & Iglesias 2015).

Dalton et al. (2012) and O'Connor et al. (2013) state that 10 % of the initial cost can be used as a first estimate for the cable costs. According to Farrell et al. (2015) and O'Connor et al. (2013a) the costs of the underwater cables for installations smaller than 20 MW

(33-38 kV) is 173 000 €/km and for farms over 20 MW (110 kV) the cost is 288 000 €/km. Farrell et al. (2015) state that also a rock coverage is needed for the cabling for the first kilometer, which costs 939 000 €. All cable cost estimations are gathered in table 20.

Table 20. Cable costs.

Cable type	Cost	Source[a]
All cables	10 % CAPEX	A
Underwater Cable	173 €/m (< 20 MW) 228 €/m (> 20 MW)	B, C
Rock cover	939 000 €/km	C

[a]A: Dalton et al. 2012, B**:** O'Connor et al. 2013a, C: Farrell et al. 2015

Other big cost creators are the substations. The substations correct the electricity signal so that it can be fed to the electrical network. With offshore wave energy converters, such as the Penguin, the signal need to be modified twice before entering it to the grid. On the offshore substation, the voltage is increased for sending it to the onshore substation as can be seen in figure 9. The current can be sent either alternating (AC) -or direct (DC). Most efficient solution is High Voltage Direct Current (HVDC), but that is also the most expensive one. When using DC, costly AC/DC converters are needed, both offshore and onshore, before entering the current into the grid. Since distances to shore are often not greater than 5 km, the most economical solution to date is to use High Voltage Alternating Current (HVAC). (Astariz & Iglesias 2015) The HVAC system is the most used with offshore solutions. It is well known, stable and mature technology.

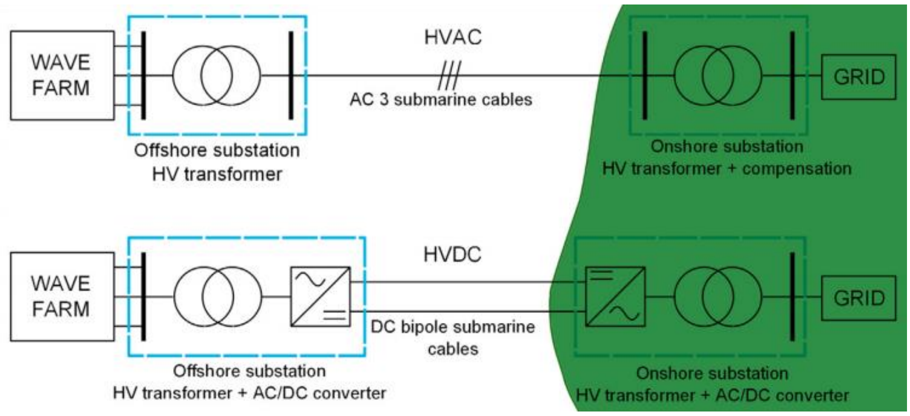

Figure 9. Offshore wave energy power transmission (Lopez et al 2013).

Farrell et al. (2015) estimate the price for the underwater HVAC substation to be between 48 000 and 79 000 €. According to O'Connor et al. (2013a) the onshore substation costs 20 000 €/MW with HVAC applications. In addition a floating substation for less than 5 MW installation costs 0.5 M€ and another 0.3 M€ for connections. For installations greater than 5MW the total cost is estimated to be 0.6 M€/MW. (O'Connor et al. 2013a) Therefore, according to O'Connor et al. (2013a**),** an undersea power substation would be the less costly solution. The substation costs can be seen in table 21.

Table 21. Substation costs.

Substation	Cost	Source[a]
Floating	0,8 M€ (<5MW)	A
	0,6 M€/MW (>5MW)	A
Underwater	48 000 - 79 000 €/park	B
Onshore	20 000 €/MW	A

[a]A: O'Connor et al. 2013a, B: Farrell et al. 2015

4.3. OPEX and decommissioning

OPEX, which consists of operations and maintenance (O&M) and insurances will most likely be a significant part of the costs of wave power. O&M costs include:

- Maintenance
- Site rent
- Other rents
- Annual impact statement

Farrell et al. (2015) state that O&M expenditures create a great uncertainty in the profitability of any early stage wave energy system. They state that the WEC -and the installing costs can be extrapolated (through industry benchmarking) to a certain level with relative certainty. O&M expenditures, on the other hand, are hard to predict. (Farrell et al. 2015) Most of the cost estimates are based on benchmarking oil, gas and offshore wind industries. The existing estimates are presented in relation to the power produced and others as a percentage of CAPEX or OPEX.

Dalton et al. (2010 and 2012) use 1 - 3 % of the IC for O&M and insurance each. Previsic (2004) and Allen et al. (2008) have estimated all OPEX to be around 40 % of all wave farm lifetime costs. Farrell et al. (2015) estimated OPEX to be between 4 and 10 % of IC annually with insurance and O&M causing equal costs. Lastly Wello Oy provided an estimation of 100 000 – 300 000 €/year (Personal communication with Wello presentative).

The plant also needs to be dismantled after its use. The cost of dismantling is estimated to be around 1 % of the IC (SI OCEAN 2013). Climate Change Capital (2010) evaluated the decommissioning cost to be about 50 000 €/MW in 2010 prices. In addition to the other annual costs, the mooring change costs need to be taken into account as described before.

Below in table 22 are presented the estimations for operations and maintenance expenditures as are the insurance –and decommissioning expenditures. Notable here is that the cost estimations are benchmarked from offshore wind –and oil industry. The maintenance operations in these industries are typically done offshore and at the location. Operations and maintenance for the Penguin can be done inside the vessel and therefore no towing or other actions are needed for access. Accessible wave height is 1.5 to 2 meters depending on the size of the ship. In addition the underwater parts, such as anchoring and cable connection can be maintenanced and changed from the surface. Therefore the similarities are clear and the benchmarked estimations are more accurate for the Penguin than what they are for the Pelamis P1. The P1 operations are not performed at the location, but the WEC is towed to the shore for maintenance.

Table 22. Operating & Maintenance + decommissioning.

O&M and decommissioning	Costs	Source[a]
O&M	1-3 % of IC per annum for 20 years	A, B
	2-5 % of IC per annum for 15 years	C, D
Insurance	1-3 % of IC per annum for 20 years	A, B
	2-5 % of IC per annum for 15 years	C, D
OPEX	40 % of project total cost	F, G
	100 000 - 300 000	H
	50 000 €/MW	I
Decommissioning	1 % of IC	E

[a] A: Dalton et al. 2012 B: Dalton et al. 2010, C: Farrell et al. 2015, D: O'Connor et al. 2013a, E: SI OCEAN 2013, F: Allen et al. 2008, G: Previsic 2004, H: Personal communications with Wello presentative, I: Climate Change Capital 2010.

In the next chapter, chapter 5, all of the factors presented in this chapter (4) and in chapter 3 are combined and analyzed in order to estimate the feasibility and financial potential of The Wello Penguin wave energy converter.

5. FEASIBILITY OF THE WELLO PENGUIN WEC

5.1. Current costs of Wello Penguin

In this chapter the focus is on the feasibility and on the economic potential of Wello Penguin wave energy converter. Below in table 23 are presented three cost scenario estimations for investment -and operational costs for one Penguin wave energy converter, based on the values presented in chapter 4**.** The scenarios are: best case, worst case and estimated. Some of the researched material, presented in chapter 4, showed some differentiation in the cost estimations and therefore some of the estimations need to be given more weight than the others.

First in table 23 are the pre-operating costs. The cost range of 0.5 - 2 M€/MW have been used as suggested by Farrell et al. (2015) since Dalton et al. (2012) suggestion of 10 % of CAPEX fits inside this limit as can be easily seen from table 23. In the early stages of the development the pre-operating costs are hard to predict due to the lack of experience and are therefore causing a lot of uncertainty. For the licenses and permissions there was no deviation in the reference material and the costs are estimated to be 2 % of WECIC as stated by Astariz & Iglesias (2015) and Dalton et al. (2012). For GHG investigations a value of 1 % of WECIC has been used as suggested by Dalton et al. (2012). The chosen WECIC estimations are provided by the developer (personal communications with Wello presentative). Recent and accurate estimations could be found both for the cable costs and for the substation costs and therefore the estimations provided by O'Connor et al. (2103a) and Farrell et al. (2015) were used. In the calculations an assumption is made that the cable cost connecting the WECs is 173 000 €/km.

The methods of calculating the operational expenditures varied somewhat. The more recent studies by O'Connor et al. (2013a) and Farrell et al. (2015) gave the same estimations of 2 -5 % of IC for both O&M and insurance, when Dalton et al. 2010 and 2012 estimated them to be between 1 and 3 %. Allen et al. (2008) and Previsic (2004) suggested another approach to estimate the OPEX, as the percentage of the total project lifetime costs. Due to the older material and unpractical method this approach is not taken into consideration and the recent estimations of 2 - 5 % of IC is used. Also the estimation provided by the developer are neglected at this point. The decommissioning cost of 1 % of IC is used. SI OCEAN (2013) estimated it to be some 50 000 €/MW and as can be seen from table 23 the decommissioning estimations are similar with both methods.

The three cost scenarios, gathered in table 23, should give the limits of where the costs would be in a full scale installation at a current state (2015). Table 23 shows that the total initial costs for one Penguin 1 MW converter lie between 4.5 and 6.6 M€ and the annual costs are between 223 149 and 557 972 €. Added to these costs are anchoring chain changing costs, that need to be done every 7 years. Anchoring change costs are estimated to be 80 % of the original mooring costs and are adjusted with inflation as are the decommissioning costs (calculated according to equation 8). The inflation rate used throughout the calculations is chosen to be 2 % according to the long term average European inflation rate. An assumption is made that the rates will increase soon in the near future.

Table 23. Three installation price scenarios for one Penguin WEC.

Category					
Pre operating costs	Min. Cost	Estim. Cost	Max Cost		Source
Pre operating costs	500 000	1 250 000	2 000 000	500 000-2 000 000€/MW	A
Licenses and permissions	50 000	55 000	60 000	2 % of WECIC	A, B
GHG Investig.	25 000	27 000	30 000	1 % of WECIC	B, C
WEC					
WEC	2 500 000	2 750 000	3 000 000	2 500 000 – 3 000 000 €	D
Mooring					
Hardware	250 000	275 000	300 000	10% of WECIC	A, B, C, E, I
Installation		35 226		5871 €/day, 6 days	G
Connections					
Underwater cable		173 000		173 €/m, 1000 m (<20MW)	F, G
		228 000		228 €/m (>20 MW)	F, G
Rock cover		939 000			G
Offshore substation	47 000	55 000	59 000	47 000-59 000 €	G
Onshore substation		20 000		20 000/MW	F
IC total	4 539 226	5 579 726	6 616 226		
OPEX + Decom.					
O&M + Insurance	223 189	390 580	557 972	2-5% IC O&M, 2-5 % IC Insur.	F, G
Decommissioning	45 392	55 797	66 162	1 % of IC	H

[a]A: Astariz & Iglesias 2015, B: Dalton et al. 2012, C: Dalton et al. 2010, D: Communications with Wello presentative, E: Allen et al. 2013, F: O'Connor et al. 2013a, G: Farrell et al. 2015, H: SI OCEAN 2013

The cost estimations make the assumptions that the total cable need is 1 km. The actual distances of the sites, presented in chapter 3, are not used since the locations of the test sites have not been selected in order to maximize the feasibility for wave power applications. In installations of multiple WECs the distance between WECs is fixed to 100 m as stated by Dalton et al. (2012).

Figure 10 and table 24 present the lifetime costs of one Penguin 1 MW wave energy converter. The costs are calculated from an active use of the WEC during 20 years with an annual discounting factor of 5 % and with the average cost scenario (table 23).

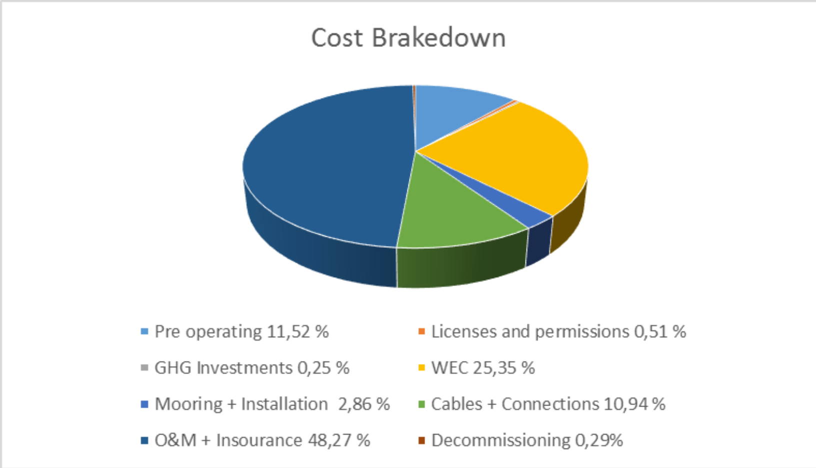

Figure 10. Lifetime cost distribution of Penguin for 1 MW installed.

The O&M and insurance (OPEX) are the biggest causes of costs creating almost half of the lifetime costs. The second biggest cost is the WECIC by 25.35 %, followed by the pre operating expenditures with 11.52 % and cables and connections with 10.94 %. All of the rest causes less than 4 % of the lifetime costs. The total lifetime cost for one WEC with a 1 MW power rating is 10 846 471 €. Appendix 3 presents the excel spreadsheet on which the calculations are based.

Table 24. Lifetime cost distribution of Penguin for 1 MW.

Cost Breakdown	€/MW
Pre operating	1 250 000
Licenses and permissions	55 000
GHG Investments	27 500
WEC	2 750 000
Mooring + Installation	310 226
Cables + Connections	1 187 000
O&M + Insourance	5 235 497
Decommissioning	31 249
Total	10 846 471

The differences in cost structures within installations of different sizes were explained in chapter 4. The main differences that are predictable and easily measured are the cable and connection costs. Table 25 and figure 11 show the cost structure of a 100 MW installation. The calculations have been made the same way as before with the 1 WEC installation estimation. Figure 11 shows that cables and connections now only cause for 0.99 % of the total costs with 96 570 €/MW.

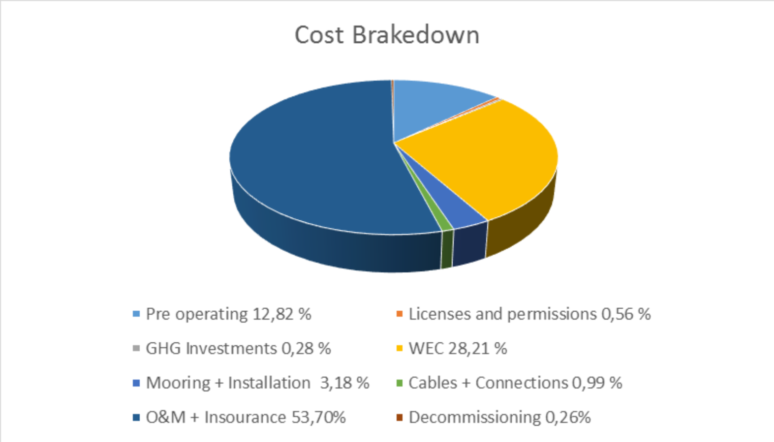

Figure 11. Lifetime cost breakdown of Wello Penguin 100 MW installed.

In the 100 MW installation the total lifetime cost is 9 749 935 €/MW. Notable factor here is that the O&M expenditures per megawatt are presented as equals for 100 MW and 1 MW installations. In reality it is likely that the O&M expenditures would be smaller in larger installations, since many of the operations can be performed on multiple WECs during one departure of the vessel. This will be taken into account later in this chapter, when the learning based method is used.

Table 25. Lifetime cost breakdown of Wello Penguin 100 MW installed.

Cost Breakdown	€/MW
Pre operating	1 250 000
Licenses and permissions	55 000
GHG Investments	27 500
WEC	2 750 000
Mooring + Installation	310 226
Cables + Connections	96 570
O&M + Insourance	5 235 497
Decommissioning	25 142
Total	9 749 935

In table 26 are calculated lifetime feasibility estimations for 1, 20 and 100 WECs with the three cost scenarios presented in table 23. In addition the calculations have been made with three different annual energy output levels. The outputs are based on the Belmullet energy resource, which is the energy richest location and will also create the largest annual outputs from the Penguin with all of the maximum availability levels. The used maximum availability levels are: 97, 97.5 and 98 % and the cut in wave height limit is 1 m. The used wave energy capture ratio is the current 20 % of the 23.4 m machine width. The according annual energy levels are: 1138.7, 1445.3 and 1762.5 MWh/year. A discount rate of 8 % has been used for 1 and 20 MW installations and the 100 MW wave park estimations are calculated with 6 %. The 8 % (for small installations) and 6 % (for larger installations) discount rates are often cited in literature as described in chapter 2.4

(O’Connor et al**.** 2013a, O’Connor et al. 2013b, Lopez et al. 2013, Farrell et al. 2015). The used feed in tariff for these calculations is 350 €/MWh, according to the planned Irish FIT (Dalton et al. 2012). The tariff is fixed and will not be adjusted with inflation over time as describe in chapter 2.5**.** Otherwise the same methods have been used as before, when estimating the lifetime costs.

The average NPV is negative 3.82 M€/MW and the average COE is 626.7 €/MWh. Table 26 shows that the only positive results are created when the maximum availability is 98 % and the cost scenario is the “minimum cost”. In addition the installation size need to be the large 20 or 100 MW. The IRR’s of these two installations are 9 % with the 20 MW park size and 9.2 % with the 100 MW installation size. The net present values are 265 567 and 920 208 €/MW and COEs 334 and 304 €/MWh accordingly. Since out of these 27 scenarios only two give a positive result, it looks clear, that the converter is not yet able to compete commercially even in high FIT situations. In addition the maximum availability of 98 % at this early stage is unlikely, to say at least.

Table 26. Feasibility of Penguin WEC in 2015.

	Estim. cost			Min cost			Max cost		
	1 WEC	20 WEC	100 WEC	1 WEC	20 WEC	100 WEC	1 WEC	20 WEC	100 WEC
	Max avail 97 %								
NPV €	-5 684 226	-4 577 476	-4 565 506	-2 979 537	-1 878 029	-1 584 019	-8 384 906	-7 271 973	-7 539 814
COE €/MWh	858,4	759,4	699,6	616,5	518,0	471,3	1 099,9	1 000,4	927,3
IRR									
	Max avail 97,5 %								
NPV €	-4 630 641	-3 524 921	-3 335 873	-1 926 983	-825 475	-354 386	-7 332 351	-6 219 419	-6 310 181
COE €/MWh	676,3	598,5	551,3	485,8	408,2	371,4	866,8	788,4	730,7
IRR				1,49 %	4,54 %	4,67 %			
	Max avail 98 %								
NPV €	-3 544 638	-2 431 706	-2 057 749	-835 941	265 567	920 209	-6 241 310	-5 128 377	-5 035 586
COE €/MWh	554,8	490,5	451,8	398,3	334,7	304,5	710,7	646,4	599,1
IRR				5,39 %	9,03 %	9,19 %			

The NPV and COE results from table 26 are presented graphically in figure 12. The data is presented in the same order as in table 26**.** From left to right first are presented all estimations with 97 % maximum availability values and starting cost scenarios in order: estimated, minimum and maximum, followed by 97.5 and 98 maximum availability levels.

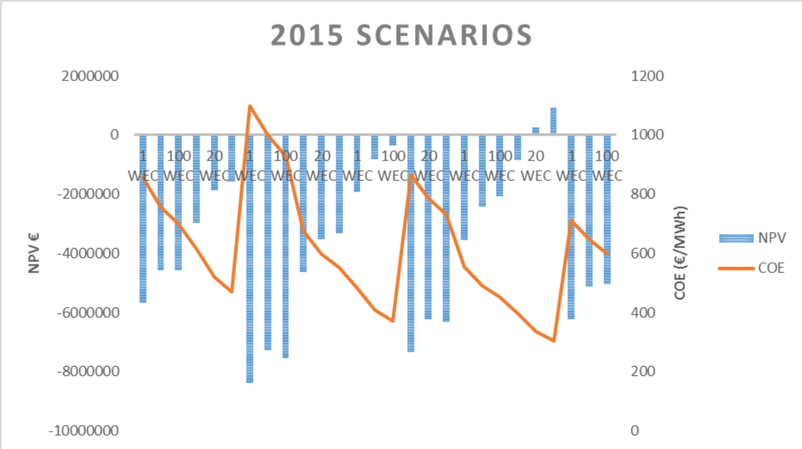

Figure 12. Cost of electricity and net present value for 1, 20 and 100 unit installations in different scenarios in 2015 costs.

Even though the Penguin wave energy converter is not yet at the commercial stage, an interesting question is whether it has the potential to become one. In the next chapter **(5.2)** the future potential of the Penguin is being analyzed.

5.2. Future costs of Wello Penguin installations

The goal for Wello Oy is to develop the Penguin WEC so that it would be commercially ready and able to compete with other methods by the year 2030 (Personal communications with Wello presentative). Many literature references also state that commercial success need to be achieved within the next 15 years in order for the technology to succeed. If the development process will prolong it would increase the changes that the interest towards wave power would decrease. (Dalton et al. 2012, O'Connor et al. 2013, Ferrell et al. 2015) The timeframe of this work is based on that 15 year assumption. Accordingly a scheme, or installation plan, has been made in order to estimate the feasibility of wave power by the year 2030. The installation plan is presented in table 27 and it follows the views and goals stated by Wello Oy (Personal communications with Wello presentative). The plan consists of three distinct phases with clear step ups in the installation sizes. It makes the assumption that the megawatt rating of a single WEC does not get any greater. In the first phase, which is from 2016 to 2020, the first multi WEC installations are made. Between 2020 and 2026 the first larger installations, with cumulative power ratings from 20 to 25 MW per farm, are made. Lastly in the final stage three large 100 MW wave farms are made. The estimations for future costs are based on the learning rate method (equation 9 and 11), described in chapter 2.8. With this installation plan and the learning rate method cost estimations are able to be drawn for the development time, and for what should be an industrial product at the end of the scheme.

Table 27. Installation plan of Wello Penguin.

	year	MW	Cumulative
Existing (MW)		3	3
1st phase	2016	3	6
	2018	4	10
	2020	6	16
2nd phase	2022	20	36
	2023	20	56
	2024	25	81
3rd phase	2026	100	181
	2028	100	281
	2030	100	381
	Total	381	

In figures 13 and 14 the cost development curve estimations have been drawn. There are three IC estimations for the current costs following the cost creation rules of table 23. The starting initial costs are based on the megawatt costs of a 100 WEC installation. As mentioned in chapter 2.8., Dalton et al. (2012), and Ferrell et al. (2015) have suggested that a learning curve factor of 85 – 90 % is arguably correct with wave power cost estimations. In figure 13 and 14 two learning curve factors have been used accordingly (85 and 90 %) and equations 9 and 11 have been applied to achieve the estimations. An assumption is made that Wello Oy has already developed WECs for a cumulative power of 3 MW, as is stated also in table 27.

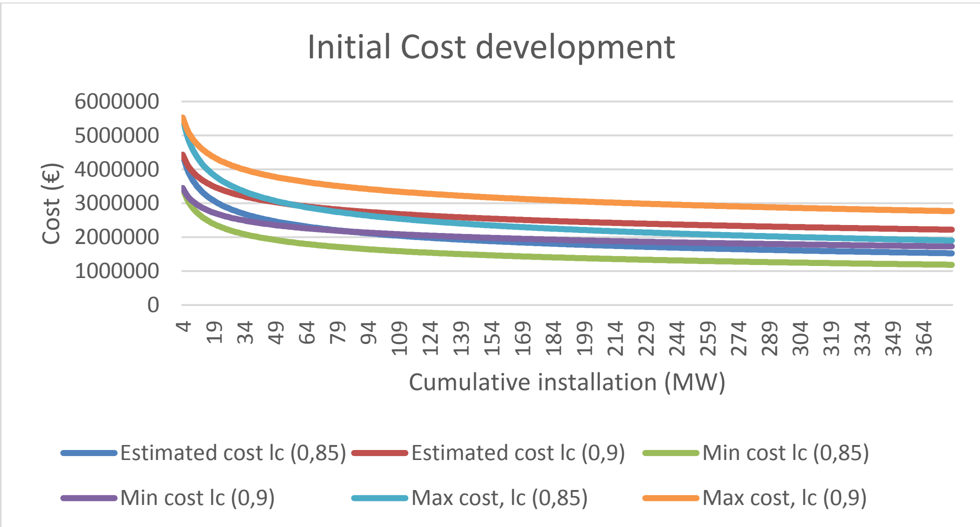

Figure 13. Estimated IC development for one MW in 100 WEC figuration.

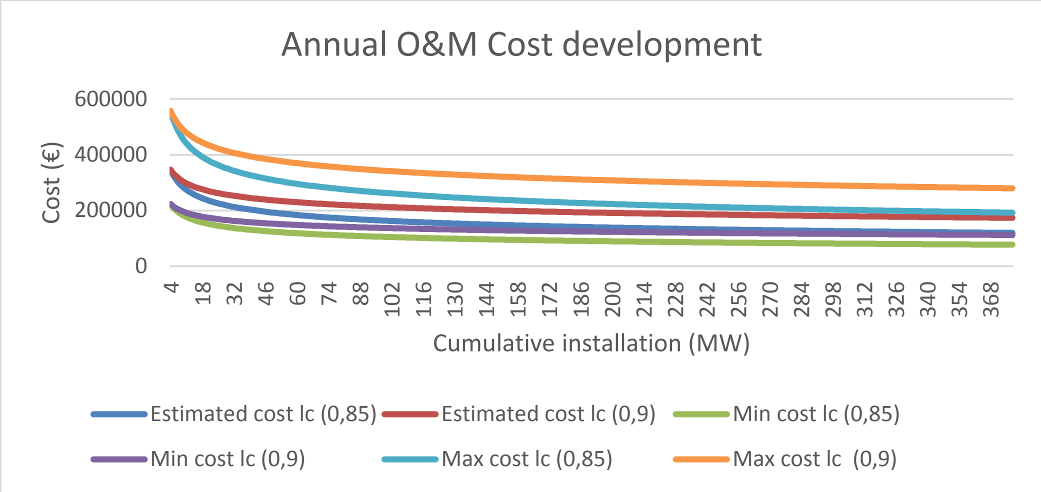

Figure 14. Estimated annual O&M cost development for one MW in 100 WEC figuration.

Figures 13 and 14 show that the initial cost after 381 MW's of installations is between 2.8 and 1.2 M€/MW and the annual O&M and insurance costs are between 80 000 and 280 000 €. The average IC of these scenarios is 1 885 848 €/MW and for O&M and insurance the annual cost would be 158 561 €/MW. All of the calculated cost outcomes are presented in table 28. These costs are in 2015 prices, since equation 9 does not take the devaluation of currency into account. The estimated costs are in €/MW in 100 MW wave park.

Table 28. Estimated costs after 378 (+ 3) MW of installations for 100 MW Park.

	Initial Cost [€]	O&M + Insurance [€/MW]
Estim. Cost, *lc* 0,85	1 523 525,1	119 013,1
Estim. Cost, *lc* 0,9	2 218 355,2	173 291,1
Min cost, *lc* 0,85	1 184 929,3	76 669,0
Min cost, *lc* 0,9	1 725 336,9	111 635,3
Max cost, *lc* 0,85	1 898 540,1	191 672,6
Max cost, *lc* 0,9	2 764 402,3	279 088,2
Average	1 885 848,1	158 561,5

The feasibility can now be estimated with the new cost estimations. The same Excel spreadsheet has been used as before. At this point a discount rate of 6 % has been used as explained by Dalton et al. (2012): 6 % can be used for large installations (Dalton et al. 2012) and for smaller installations 8 % more appropriate (O'Connor et al. 2013a and Farrell et al. 2015). The future cost scenarios of table 28 were used to calculate the feasibility in 2030 level by using the according value pairs of IC and O&M & insurance together. The feasibility measurements are same as before: NPV, COE and IRR. The anchoring change -and decommissioning costs are not included in the values presented in table 28 and therefore they need to be added in the calculations. They both are corrected with the percentage scaling of the learning factor and with 2 % inflation. First in table 29 and figure 15 the feasibility estimations (per megawatt installed) have been made with the average IC -and O&M and insurance costs in 2030 cost levels.

Table 29. Feasibility estimation for 100 WEC installation in 2030 in average cost scenarios.

Location				
	capture efficiency	20 %	25 %	30 %
North sea	NPV	-3 220 945	-3 046 063	-2 873 398
	COE	448,4	358,7	299,5
	IRR			
M4	NPV	-2 177 388	-1 816 241	-1 485 884
	COE	179,9	149,1	128,8
	IRR			
Lisboa	NPV	-2 606 476,7	-2 287 505,5	-1 979 783
	COE	238,7	192,1	161,6
	IRR			
Belmullet	NPV	-1 787 411,1	-1 374 803,2	-1 004 194
	COE	147,0	123,2	107,5
	IRR			
EMEC	NPV	-3 193 464	-3 025 554	-2 863 229
	COE	431,4	350,5	296,7
	IRR			

All five locations have been used in the calculations with 20, 25 and 30 % capture efficiencies. The maximum availability level used here was the high 99 %. Table 29 shows that all of the scenarios have a negative NPV. The NPV and COE are presented graphically in figure 15. Feed in tariff used here was 80 €/MWh but notable factor is that there is high uncertainty related to it. Therefore the most interesting and important value here is the COE. The COE changes between 448 and 108 €/MWh. Negative IRR values are not presented.

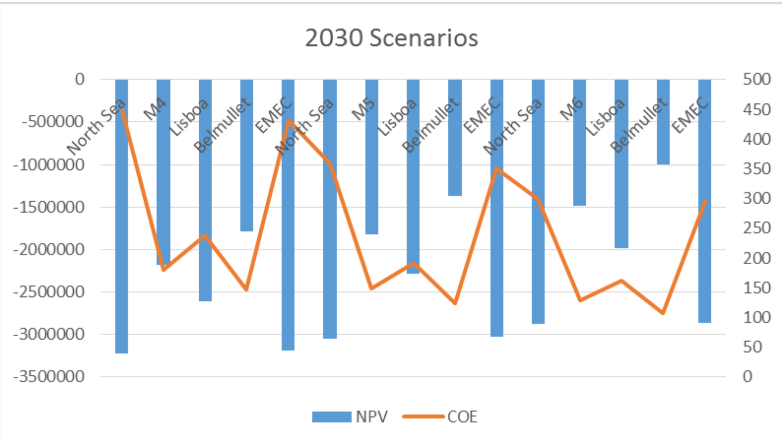

Figure 15. Feasibility estimation for 100 WEC installation in 2030 in average cost scenarios in order of 20, 25 and 30 % capture efficiency from left to right.

Two of the scenarios in Belmullet energy resource create COE's under 120 €/MWh. The values are 123 and 107 €/MWh with the 25 and 30 % capture efficiencies and in unlikely but yet possible FIT situations these 2 (out of 9) values could be feasible.

Next all the rest of the estimated cost scenarios have been used to form table 30 and figure 16 the same way as is done with table 29 and figure 15. The according IC and O&M + insurance pairs have been used with the same location -and power capture options with 99 % maximum availability. The used feed in tariff is the same 80 €/MWh as before and the discounting rate is the same 6 %. Table 30 shows that three different scenarios give a positive NPV (out of 60), which means that the three scenarios have COE's under 80 €/MWh. Again the feed in tariff creates uncertainty, which means that the COE is the most important value here. Total of 8 different combinations make a COE less than 100 €/MWh and totally 17 different combinations make a COE under 120 €/MWh.

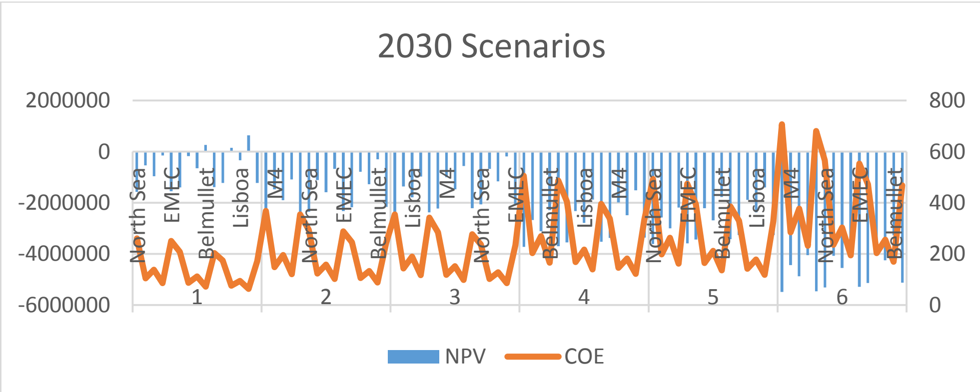

Figure 16. All feasibility scenarios for 2030.

When looking at figure 16, it gives a good idea of the importance of the energy produced. The two locations with clearly less wave energy, North Sea and EMEC, have only half of the resource of Lisboa's 38.9 W/m and less than half of M4's 53.9 and Belmullet's 69.5 W/m. The average COE from EMEC and North Sea is 354.3 €/MWh and even with the 30 % capture efficiency it is 298.1 €/MWh. Therefore these lower (medium) energy resources are clearly not enough to make profitable locations for wave energy in the near future. The average COE for Belmullet and M4 is 139.3 €/MWh and this value is already closer to the 101.3 €/MWh COE values of wind power in 2015, but are still exceeding it with almost 40 €/MWh. The average COE values for M4 and Belmullet with capture efficiencies of 20, 25 and 30 % are 163.5, 136.1 and 118.2 €/MWh respectively. With the high 30 % capture efficiency at the Belmullet resource (the highest resource) the average COE is 107.3 which already could be feasible in favorable FIT situations. Notable here is that the maximum availability level used was the high 99 % and therefore lower availability would increase the cost of electricity levels. Still this analysis gives an insight of where the COE would set in a presence of a learning curve. If the robustness issues can be overcome the 118 - 136 €/MWh COE levels could be achieved with good certainty. In addition as can be seen from table 30 and fig. 16 the under 100 €/MWh COE values are indeed possible and therefore any final conclusions of the feasibility cannot be drawn based on the analysis so far.

Table 30. Feasibility scenarios in 2030 for 100 MW installation.

Location		1			2			3		
	Capture efficiency	20 %	25 %	30 %	20 %	25 %	30 %	20 %	25 %	30 %
	Cost scheme	min cost, *lc* 85			min cost, *lc* 90			est. cost, *lc* 85%		
North sea	NPV	-1 576 930	-1 402 047	-1 229 383	-2 519 866	-2 344 984	-2 172 320	-2 403 796	-2 228 913	-2 056 249
	COE	260,3	208,3	173,9	368,2	294,5	246,0	354,9	283,9	237,1
	IRR									
M4	NPV	-533 373	-172 226	**158 132**	-1 476 309	-1 115 162	-784 805	-1 360 239	-999 092	-668 734
	COE	104,5	**86,5**	**74,8**	147,8	122,4	105,8	142,4	118,0	102,0
	IRR		4,09 %	7,64 %						
Lisboa	NPV	-962 461	-643 490	-335 767	-1 905 397	-1 586 426	-1 278 704	-1 789 327	-1 470 355	-1 162 633
	COE	138,6	111,5	**93,8**	196,0	157,7	132,7	188,9	152,0	127,9
	IRR			2,13 %						
Belmullet	NPV	-143 395	**269 213**	**639 822**	-1 086 332	-673 724	-303 115	-970 261	-557 653	-187 044
	COE	**85,4**	**71,5**	**62,4**	120,7	101,2	**88,3**	116,4	**97,5**	**85,1**
	IRR	4,42 %	8,75 %	12,22 %		0,49 %	3,69 %		0,88 %	4,41 %
EMEC	NPV	-1 549 449	-1 381 538	-1 219 214	-2 492 385	-2 324 475	-2 162 150	-2 376 315	-2 208 404	-2 046 080
	COE	250,5	203,5	172,3	354,3	287,8	243,6	341,5	277,4	234,8
	IRR									
		4			5			6		
	Capture efficiency	20 %	25 %	30 %	20 %	25 %	30 %	20 %	25 %	30 %
	Cost scheme	est.cost *lc* 90 %			max cost, *lc* 85 %			max cost, *lc* 90 %		
North sea	NPV	-3 723 054	-3 548 172	-3 375 507	-3 615 622	-3 440 740	-3 268 076	-5 486 406	-5 311 523	-5 138 859
	COE	505,8	404,6	337,9	493,5	394,8	329,7	707,4	566,0	472,6
	IRR									
M4	NPV	-2 679 497	-2 318 350	-1 987 992	-2 572 065	-2 210 918	-1 880 561	-4 442 849	-4 081 702	-3 751 344
	COE	203,0	168,1	145,3	198,0	164,1	141,8	283,9	235,2	203,3
	IRR									
Lisboa	NPV	-3 108 585	-2 789 614	-2 481 892	-3 001 153	-2 682 182	-2 374 460	-4 871 937	-4 552 966	-4 245 243
	COE	269,3	216,7	182,3	262,7	211,4	177,9	376,6	303,1	255,0
	IRR									
Belmullet	NPV	-2 289 519	-1 876 912	-1 506 303	-2 182 088	-1 769 480	-1 398 871	-4 052 871	-3 640 263	-3 269 654
	COE	165,9	139,0	121,3	161,8	135,6	118,4	232,0	194,4	169,7
	IRR		-10,28 %	-5,13 %		-14,55 %	-6,62 %			
EMEC	NPV	-3 695 573	-3 527 662	-3 365 338	-3 588 141	-3 420 231	-3 257 907	-5 458 925	-5 291 014	-5 128 690
	COE	486,7	395,3	334,6	474,8	385,7	326,5	680,7	553,0	468,1
	IRR									

Next in chapter 5.3. a closer look is taken into the installation scheme as a whole. Also as, mentioned before, the feed in tariff in 2030 will have a high importance for the feasibility of all wave power projects. This aspect will be taken into the consideration more thoroughly.

5.3. Decision tree analysis

To estimate the total NPV of the installation plan of table 27, two plausible cost scenarios have been made based on the information of table 23. The extreme scenarios of table 23 show the limits where the initial -and the annual costs would lie, but here the two scenarios are made to be more sensible and plausible. The cost scenarios are presented in table 31. Table 23 shows that mooring installation costs, cable -and cable rock cover costs and onshore substation costs are certain. In the two scenarios of table 31 these costs are also fixed. Licenses and permissions, GHG investigation -and offshore substation costs on the other hand are small compared to the total IC, so these cost changes are kept the same as previously in table 23. The two remaining substantial initial cost elements with large uncertainty are pre operating costs (excluding licenses and permissions -and GHG investigation costs) and OPEX. In table 23 the pre operating costs change between 0.5 M€ and 2 M€, which averages at 1.25 M€. Therefore the change from the average value is 60 %. For table 31 the plausible change is set to be 20 %, creating costs of 1 and 1.5 M€. In addition, when the WEC cost change is set to be the same (2.5 – 3.0 M€) the total change in relation to the estimated IC is 9.6 %, when in table 23 the change is 18.6, for 1 MW installation %.

There is even more uncertainty in the annual costs than in the initial costs. The decommissioning costs are not significant for the total lifetime costs and therefore no uncertainty is put into it. The decommissioning costs are estimated to be 1 % of the estimated average IC (table 23). The annual O&M -and insurance costs on the other hand have a high effect on the feasibility. In the three scenarios of table 23 both the O&M –and the insurance costs each changed between 2 and 5 % of the IC. For the plausible scenarios the percentage values are based on the estimated average IC cost (of table 23, 5 579 726 €) and the chosen percentages are 2.5 and 4.0 % for O&M and insurance each. Instead of choosing symmetrically 3 and 4 % the optimistic scenario has been lowered to 2.5 according to personal contact with the developer (Wello estimated the annual costs to be between 100 000 and 300 000 €). The chosen percentages create annual costs of 278 986 and 446 379 €, which are still higher than the values stated by the developer, but follow more the estimations on literature.

Next, based on the installation plan of table 27 a decision tree model has been created. According to the installation plan, the decision tree has three phases and at the beginning of every phase a growth option is present. The decision tree model is presented in figure 17. The analysis is based on the same Excel spreadsheet as the previous estimations but with the difference that the installations take place in different times. Several assumptions are made regarding the model: The IC and the O&M + Insurance costs are adjusted with a 2 % inflation factor, as are the decommissioning and mooring change costs. The learning factor is used at the beginning of every wave park installation on the IC and on the first OPEX. The learning factor is not used to make a separate cost for every WEC, but the same price is used for the whole wave park, based on the cumulative megawatt number of the last WEC. For example in the first phase the same IC and OPEX costs are used for the first 3 MW installation and second costs for the following 4 MW and so on. The learning factor is used on the OPEX only in the beginning of the park lifetime, based on the assumption that OPEX is highly connected to the WEC design and cannot be changed greatly during the WEC lifetime. This being said, the OPEX costs are adjusted with inflation only once, at the beginning of the installation, instead of doing it annually. Therefore an assumption is made that the OPEX costs are declining at the same speed with the inflation through learning during wave park’s lifetime.

Table 31. Plausible cost scenarios for Wello penguin in 2015.

Cost unit	Optimistic [€]	Pessimistic [€]	Explanation
Pre operating costs			
Pre operating (exclude. below)	1 000 000	1 500 000	20 % change of estimated
Licenses and permissions	50 000	60 000	2 % of WEC price
GHG Invest	25 000	30 000	1 % of WEC
WEC			
WEC	2 500 000	3 000 000	2 500 000 (3 000 000) €/MW
Mooring			
Hardware	250 000	300 000	10 % WEC
Installation	35 226	35 226	6 days needed 5871 €/Day to install
Connections			
Underwater cable	173 000	173 000	1000 m to shore 173 €/m < 20 MW 228 €/MW >20MW
Rock cover	939 000	939 000	Fixed cost
Offshore/Underwater	47 000	59000	47000 (59000) €
Onshore substation	20 000	20 000	Fixed cost €/MW
IC Total	**5 039 226**	**6 116 226**	
CAPEX + Decommissioning			
O&M + Insurance	278986	446 378	2,5 – 4,0 % of estimated IC for both O&M and Insurance
Decommissioning	55797	55797	1 % of original estimated IC

Two different and separate scenarios are made based on the annual energy output. In these scenarios the annual energy outputs are based on the energy resources of the Belmullet - and the M4 sites. The assumption is that the maximum availability for the installation grows in stages according to table 27 and figure 17**.** The first phase maximum availability is 97.5 %, which is the average of the cited 97 and 98 % for immature technology (Van Bussel 2009). Second phase is 98.0 % and last phase is the mature maximum availability of 99 %, as explained in chapter 2.2. Another assumption is made about the energy capture efficiency: The energy capture ratio is assumed to grow from 20 % to 25 % and finally to 30 % according to the installation phases. The two annual energy output scenarios are presented in table 32. As before, 8 % discounting values are used for installations under 100 MW, which means the two first phases. In the last phase a discounting value of 6 % was used. The feed in tariffs are also changing according to the installation phases. For the first phase a FIT of 350 €/MWh has been selected according to Scotland's planned tariff (table 3). For the second phase a tariff of 130 €/MWh was selected matching Portugal's promised tariff for cumulative installations from 21 to 100 MW. These tariffs of the first two phases are considered certain. The last phase will have two different possibilities for the tariffs.

Table 32. The two annual energy output scenarios.

			Belmullet	M4
FIT (€/MWh)	max availability	capture percentage	Energy (MWh)	
350	97,5	20 %	1 445	1 254
130	98	25 %	2 103	1 800
100/70	99	30 %	3 178	2 653

In the decision tree model (fig. 17) the first branch, starting from “investment decision 1”, means the two different initial cost scenarios according to table 31**.** After this, the costs can develop according to the learning curve factors of 85 or 90 %. After the first phase’s installation of 3 + 4 + 6 MW a growth option is present (Investment decision 2). From here the costs can yet again take the development according to 85 or 90 % learning curve factors. After the second phase a growth option is present the second time. An assumption is made that during the “investment decision 3” the last phase FIT is already known. This is why fig. 17 separates 4 times in the las branch and the investment decision can be made under this knowledge. A close up of the last phase is presented in fig. 18. Two different scenarios are made for the last phase FIT: a negative scenario of 70 €/MWh and an optimistic scenario of 100 €/MWh.

The first two FITs are not adjusted for inflation, since most likely the FIT amounts will decline with inflation until they will be lowered according to the policies in clear steps (Dalton et al. 2012). The only exception is the last phase’s tariff. It is not seen as a part of any announced plan by any country, but as a more permanent level for the tariff. Therefore it is adjusted with inflation at the starting point of the last phase.

With these assumptions the two scenarios are made for the two selected locations. Tables 33 and 34 present the different outcomes from the decision trees. More detailed data of the installation development is presented in appendix 4**.** The numbers from 1 to 32 in tables 33 and 34 point the outcome possibilities of the decision trees. Number 1 is the best case, therefore the rightmost value and number 32 is the worst case and hence the leftmost outcome in fig. 17.

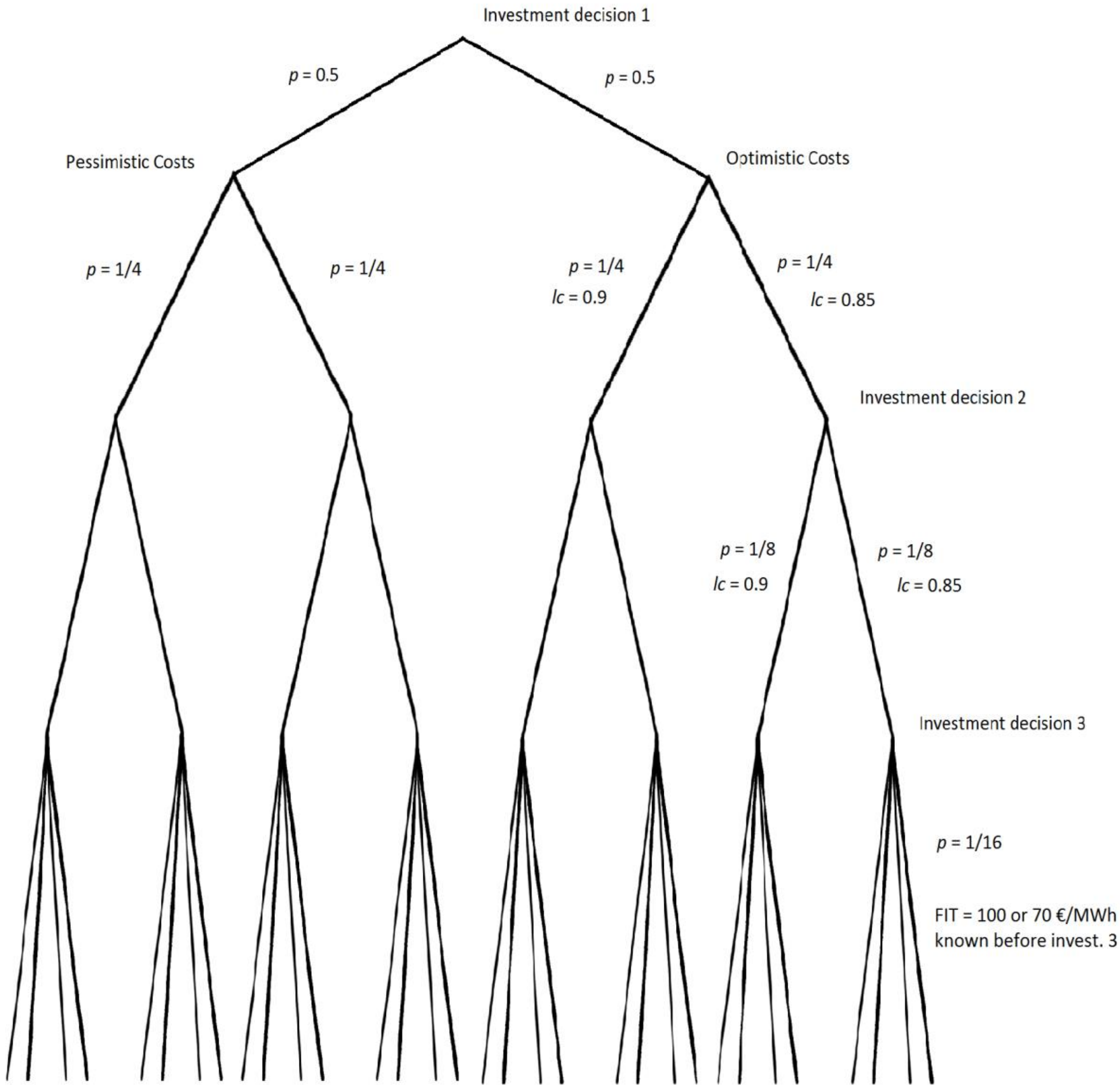

Figure 17. Decision tree model for 379 MW installation in three stages.

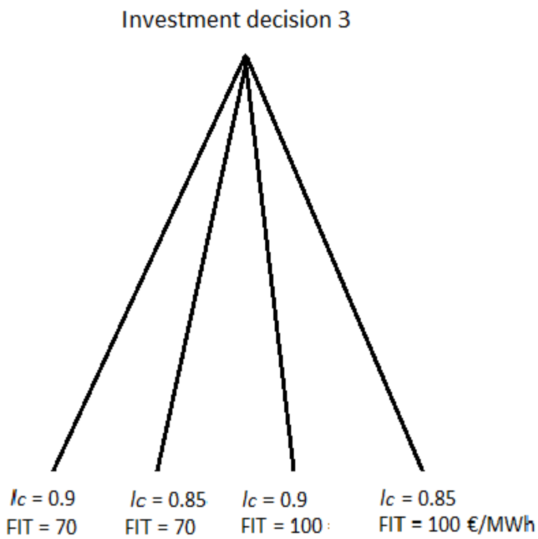

Figure 18. Investment decision 3 explanation.

Table 33. Scenario outcomes of the decision tree in Belmullet resource.

	pospospos+	pospospos-	posposneg+	posposneg-	Posnegpos+	posnegpos-	posnegneg+	posnegneg-
Optim. Cost	1	3	2	4	5	7	6	8
NPV	100 264 942	-103 381 686	51 699 171	-151 947 457	-9 616 431	-213 263 059	-67 669 148	-271 315 776
COE	123,9	123,9	130,9	130,9	141,5	141,5	149,9	149,9
IRR	8,47 %	3,01 %	7,26 %	1,73 %	5,74 %		4,47 %	
	negpospos+	negpospos-	Negposneg+	Negposneg-	negnegpos+	negnegpos-	negnegneg+	negnegneg-
Optim. Cost	9	11	10	12	13	15	14	16
NPV	-16 018 889	-219 665 516	-51 405 879	-200 020 389	-93 095 491	-296 742 118	-150 105 211	-353 695 176
COE	143,1	143,1	152,0	152,0	155,2	155,2	163,5	163,5
IRR	5,57 %		4,84 %	1,51 %	3,86 %		2,58 %	
	pospospos+	pospospos-	posposneg+	posposneg-	Posnegpos+	posnegpos-	posnegneg+	posnegneg-
Pessim. Cos	17	19	18	20	21	23	22	24
NPV	-204 020 012	-407 666 639	-270 916 008	-474 562 636	-351 395 374	-555 042 002	-433 174 135	-636 820 762
COE	175,0	175,0	184,7	184,7	198,6	198,6	210,5	210,5
IRR	1,02 %							
	negpospos+	negpospos-	Negposneg+	Negposneg-	negnegpos+	negnegpos-	negnegneg+	negnegneg-
Pessim. Cos	25	27	26	28	29	31	30	32
NPV	-361 868 414	-565 515 042	-422 363 161	-570 977 671	-477 264 003	-680 910 630	-559 641 560	-763 288 187
COE	201,0	201,0	213,6	213,6	219,3	219,3	231,2	231,2
IRR								

At the Belmullet resource two possible outcomes give a positive net present value for the installation scheme. These values are 74.4 M€ and 23.9 M€. The decision tree routes for the positive values are created with the optimistic starting cost and by price development scenarios pos-pos-pos and pos-pos-neg in high last phase FIT situations (pos = *lc* 0.85, neg = *lc* 0.9). At the M4 resource none of the outcomes gave a positive NPV, even with the high 100 €/MWh FIT. When the NPV of the whole scenario is calculated, the optimized values with 100 and 70 €/MWh FIT are -32.26 M€ at Belmullet resource and -51.68 M€ at M4 resources. These results are calculated from a situation where the two first installations are made if the starting costs turn out low (optimistic) and the first phase learning curve factor is 0.85. The smallest losses are suffered in both cases when investing is stopped after the first phase or more accurately are never being made.

Table 34. Scenario outcomes of the decision tree in M4 resource.

	pospospos+	pospospos-	posposneg+	posposneg-	Posnegpos+	posnegpos-	posnegneg+	posnegneg-
Optim. Cost	1	3	2	4	5	7	6	8
NPV	-33 593 101	-203 602 873	-82 158 872	-252 168 644	-143 474 474	-313 484 246	-201 527 191	-371 536 963
COE	146,7	146,7	155,1	155,1	167,6	167,6	177,8	177,8
IRR	5,01 %		3,81 %		2,36 %		0,99 %	
	negpospos+	negpospos-	Negposneg+	Negposneg-	negnegpos+	negnegpos-	negnegneg+	negnegneg-
Optim. Cost	9	11	10	12	13	15	14	16
NPV	-149 876 932	-319 886 703	-189 496 599	-313 564 054	-226 953 534	-396 963 305	-283 963 254	-453 916 364
COE	169,5	169,5	180,1	180,1	183,9	183,9	193,9	193,9
IRR	2,20 %		1,41 %					
	pospospos+	pospospos-	posposneg+	posposneg-	Posnegpos+	posnegpos-	posnegneg+	posnegneg-
Pessim. Cost	17	19	18	20	21	23	22	24
NPV	-204 020 012	-507 887 826	-404 774 051	-574 783 823	-485 253 417	-655 263 189	-567 032 178	-737 041 949
COE	175,0	207,2	218,8	218,8	235,3	235,3	249,6	249,6
IRR	1,02 %							
	negpospos+	negpospos-	Negposneg+	Negposneg-	negnegpos+	negnegpos-	negnegneg+	negnegneg-
Pessim. Cost	25	27	26	28	29	31	30	32
NPV	-495 726 457	-665 736 229	-560 453 881	-684 521 337	-611 122 046	-781 131 818	-693 499 603	-863 509 374
COE	238,1	238,1	253,1	253,1	259,8	259,8	274,2	274,2

Figures 19 and 20 show the effect of the last phase FIT to the total installation scheme. In the figures the orange line shows the total NPV in situations when the second installation phase has been made if the first phase had the optimistic starting cost outcome and the learning curve factor was 85 %. The blue line shows the NPV if the second installation phase is not performed. As mentioned in the assumptions, the last phase FIT can be known only after the second phase.

Figures 19 and 20 show that in the Belmullet resource, the last phase high FIT need to reach 130.15 €/MWh to make the whole investment scenario profitable. The same value for M4 resource is 164.75 €/MWh. These needed values for the last phase FITs exceed all of the planned long term tariffs for wave power and not to mention for wind power. Therefore it seems almost inevitable that in 2030 such high tariffs would be impossible. Therefore it seems clear that making the installations described here cannot be profitable with the current Wello Penguin concept.

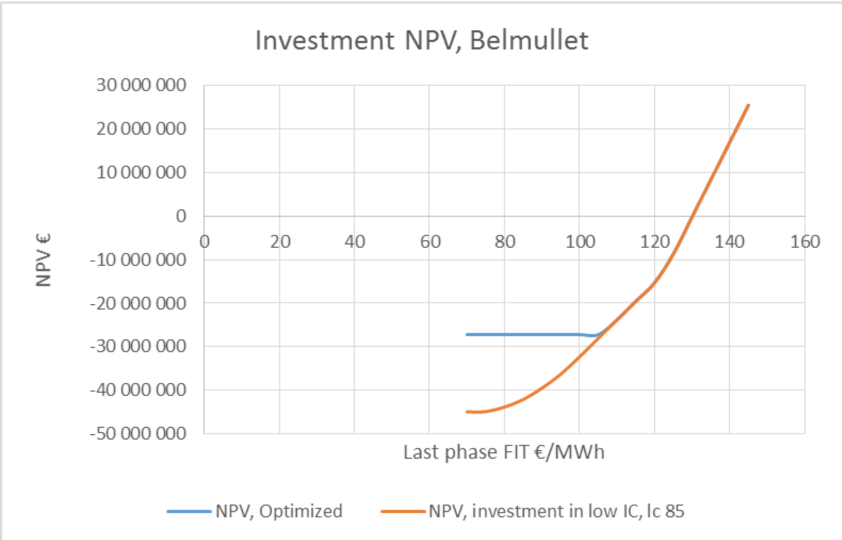

Figure 19. NPV of the decision tree in Belmullet resource.

In addition the high resource locations used in this analysis represent the highest category of possible resources that can be found in Europe. Belmullet location with its 69 MW/m present the absolute highest available resources that can be found in Europe. In addition the M4 location, which has the second highest resource out of the chosen ones, caused clearly greater losses in the overall NPV than Belmullet. Even if wave power could prove to be profitable in high energy resource atmospheres, it seems like the markets would be substantially smaller than presented in chapter 3.

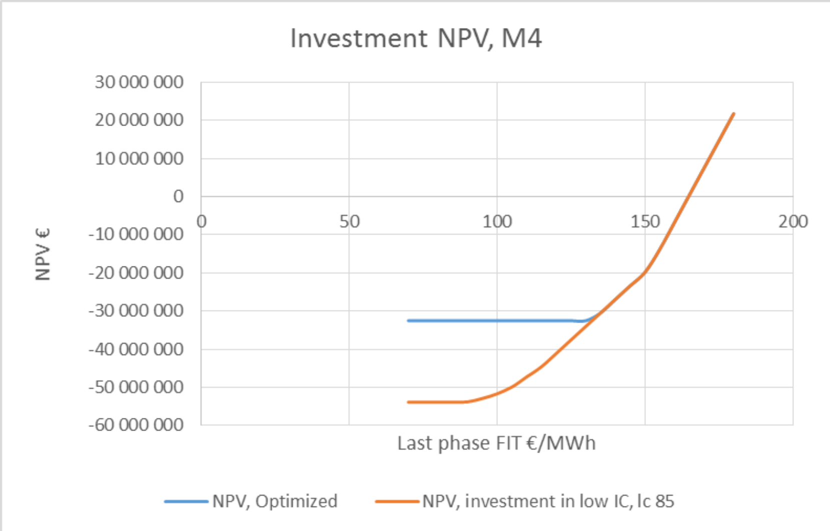

Figure 20. NPV of the decision tree in M4 resource.

The used discount rates of the installation schemes are based on benchmarked values (Dalton et al. 2012, O'Connor et al. 2013a, Farrell et al. 2015). Tables 35 and 36 were made in order to estimate the significance of the discount rates in different stages of the scheme. In table 35 the 8 % discount rate of the first two phases has been replaced with alternating values. What can be seen is that in the first stages the discounting values are not significant to the overall feasibility of the scheme. When the used 8 % discounting value vas lowered as low as 4 %, the net present value (calculated same way as in figures 19 and 20) changed between 10.2 and 4.6 %.

Table 35. Effects of the 1st and 2nd installation round discounting values.

	Belmullet	M4	Belmullet	M4
r (small installation)	NPV	NPV	Change	
8 %	-32 262 621	-51 683 139		
7 %	-31 983 392	-52 504 279	0,87 %	-1,59 %
6 %	-31 400 033	-53 205 768	2,67 %	-2,95 %
5 %	-30 429 623	-53 742 435	5,68 %	-3,98 %
4 %	-28 967 686	-54 056 480	10,21 %	-4,59 %

Table 36 shows that the last phase discount rate has a greater effect on the overall NPV of the installation scheme. Still when lowering the discounting rate as low as 4 %, the maximized NPV does not show positive values. From Table 36 can be seen the NPVs with different last phase discount rates for the two locations. In addition the needed last phase FITs for NPV(0) are calculated.

Table 36. Effects of the 3rd round installation discounting values.

	Belmullet	M4	Belmullet	M4
r (≥100 MW)	NPV €		3rd phase FIT(0) [€/MWh]	
7	-37 113 336	-53 656 910	142,67	181,65
6	-32 262 621	-51 683 139	130,15	164,75
5	-25 573 327	-49 419 251	119,00	149,85
4	-16 121 243	-45 153 434	109,99	136,75

Looking into the effects of the discount rates only makes the already made assumption stronger: the Wello Penguin wave energy converter cannot make a profitable energy production option for an energy provider in the 15 year time window. In addition, even if the 17 M€ support by European Commission's research and innovation programme Horizon 2020 is considered in the calculations, the investment scenarios still make negative NPV's. Even in the unrealistic scenario that all of the 17 M€ would go directly into the first phase installations and therefore directly to NPV, it could not make a positive NPV in neither of the locations with the excepted FIT levels.

6. CONCLUSIONS

In this master thesis the feasibility and future potential of offshore wave power has been evaluated numerically and qualitatively. For numerical estimation the selected reference wave energy converter was the Penguin concept by Wello Oy. The cost estimations are obtained by benchmarking offshore wind power and from the research on the Pelamis P1 concept in addition to the information provided by the developer. Once plausible cost estimations were made, the current price and feasibility were estimated in different wave conditions and with different robustness levels. The robustness was modelled with the maximum availability level. In the case of the current technology maturity the average NPV for a wave farm was negative 3.82 M€/MW and the average COE was 626.7 €/MWh, when a feed in tariff of 350 €/MWh was used. It looks inevitable that no installation supported only by feed in tariff can be profitable at this point.

The main timeframe for estimating the future potential was 15 years starting from 2015. An installation scheme following Wello Oy's visions was crafted with total of 379 MW installations added to the assumed 3 MW already installed. A learning based method, benchmarked on the offshore wind power and offshore oil industry, was used to estimate the cost development of the Wello concept. Throughout this work an assumption has been made that wave power should be able to compete with offshore wind power by 2030. When the feasibility was estimated at 2030 cost level, the results didn't show possibilities for open competition with offshore wind power, not to mention with any other existing methods. In the high resource locations (M4 and Belmullet) the average COE vas 139.3 €/MWh, when the 2015 COE for offshore wind power is around 100 €/MWh. In addition the wave power COE value was calculated by using the mature technology maximum availability value of 99 %, which is acquired from wind power benchmarks. Therefore a risk exists that the robustness of the WEC could not prove to be as high.

In the last phase of the numerical valuation a three phase installation analysis was made with 3 distinctive growth possibilities to estimate the total investment feasibility for the 379 MW scheme. In the model 2 plausible first cost estimations were made and 2 different learning curve rates were used. The FIT for the first 2 phases were taken from the maximum planned levels in Scotland and Portugal. The last phase was given 2 different FIT possibilities. Power capture levels were made to grow according to the installation phases from 20 to 25 to 30 % and the locations chosen were the high resource ones: Belmullet and M4. In both locations the total NPV of the scheme was highly negative. In Belmullet the NPV was -32.26 M€ and in M4 resource the NPV was as low as –51.68 M€. The last phase high FIT needed to be 130.15 €/MWh for Belmullet location and 164.75 €/MWh for M4 for the installation scheme to make a zero NPV.

In the light of the numerical estimations it seems likely that Wello Penguin wave energy converter will not be able to compete with offshore wind power by the year 2030. In addition the locational energy intensity seems to be a highly important factor for the feasibility. Therefore the high estimations of the global available wave energy resources seem to be overestimated. In addition to the need for high locational energy intensity, a high feed in tariff need to be placed for wave power to be profitable. These factors, and the habitation proximity requirements, decline the size of the potential market substantially to cover basically Scotland and Ireland in Europe.

Possibly the main advantage for wave power is be the fact that it is much more stable and more predictable than wind power. Therefore many of the problems that wind power causes for the network, due to its fluctuating production, could be minimized with wave power. This could be a reason for higher feed in tariffs for wave power. Still at this point the potential of wave power (or the Wello Penguin) does not look favorable due to its high cost of electricity. Any large or aggressive investments from any utility or investment company would have extremely high risks. There can naturally be benefits by getting into the markets first but at this point the risks overtake the possibilities.

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APPENDIX 1. PELAMIS P1 DESCRIBED

The Pelamis wave energy converter was developed and manufactured by Pelamis Wave Power (PWP), an Edinburgh based company originating from the Wave Power Group at the University of Edinburgh in 1998 (Dalton et al. 2010). The Pelamis is a semi submerged snake-like device consisting of articulated cylindrical sections linked by hinged joints (Fig. A1 and A2). The Pelamis P1 version is 120 m long and 3.5 m in diameter. The WEC is rated at 750 kW and weighs 700 tons. (Dalton et al. 2010) The assumed lifetime for a P1 is between 15 and 20 years (Dalton et al. 2010, O'Connor et al. 2013a**,** Farrell et al. 2015). Pelamis Wave Power had their first major demonstration project in Aguçadoura, Portugal. The Aguçadoura site constituted both the world's first, multi-unit wave farm and the first commercial order for wave energy converters.

Figure A1. Pelamis P1 Machine in Orkney Scotland (emec.com).

The Pelamis P1 consists of four sections that can move both vertically and horizontally. In these hinges are hydraulic cylinders that pump the hydraulic liquid into the hydraulic motor as can be seen in figure A2. All of the hydraulic cylinders are connected to the same hydraulic circle, which creates rather even flow in the circulation and therefore decreases the problem of wave's periodic nature.

The P1 can move freely in the sea according to the direction of waves. The WEC is connected to the bottom with two mooring cables that secure the anchoring. The P1 is an offshore device so offshore electricity converters are needed in addition to onshore converters.

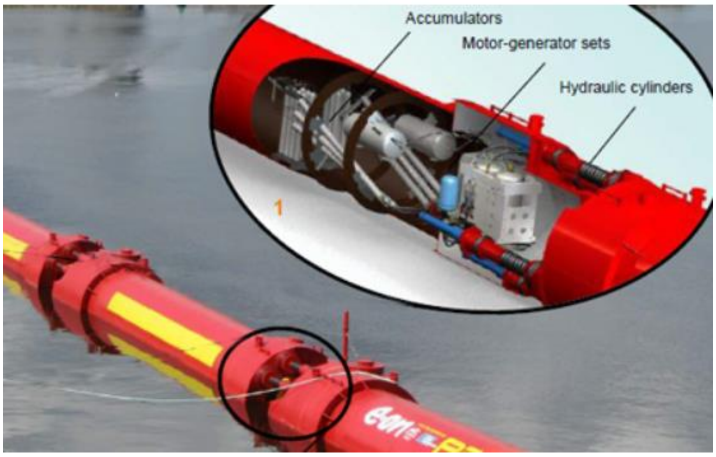

Figure A2. Cross section figure of the Pelamis hinge structure (tek-think.com**).**

The Pelamis Operations and maintenance (O&M) includes disconnecting and towing the WEC to the shore every time O&M actions need to be performed. The P1 can be accessed, disconnected and towed to the shore in wave climates under 1.5 – 2 m (Dalton et al. 2010, O'Connor et al. 2013a). The Pelamis mooring system has been repeatedly demonstrated and proved functional. The connecting requires about 2 hours and reconnecting about 15 minutes (O'Connor et al. 2013). That being said the WEC still needs to be towed to the shore every time it needs maintenance and a large towing vessel is needed increasing the O&M costs.

Pelamis P1 can produce power output in wave conditions over 1.5 m. According to O'Connor et al. (2013a) there is no upper wave height limit for the power production since the design enables the WEC to dive through the higher waves and thus keep producing on maximum power level. Still robustness issues arise in rough sea states, during winter periods, necessitating shutdowns (Dalton et al. 2010).

By 2010 Pelamis Wave Power had raised some £ 40 M from a variety of financial -and industry backers. Major stakeholders included: Emerald Technology Ventures, Norsk Hydro Technology Ventures, BlackRock Investment Managers, 3i, Carbon Trust, Nettuno Power, Tudor Global and Scottish Enterprise. Pelamis P1 is financially the most advanced WEC concept to date but yet the technology did not prove feasible enough to take it into the commercial stage. Later PWP developed an updated version of the P1 titled P2, but newer published an updated power matrix.

APPENDIX 2. POWER MATRIXES FOR 30 AND 25 % CAPTURE EFFICIENCIES

Power matrix for Wello Penguin with 30 % power capture

	Te (s)														
		1,2	2,4	3,6	4,8	6	7,2	8,4	9,6	10,8	12	13,2	14,4	15,6	16,8
Hs (m)	0,5														
	1	2,0	4,0	6,0	8,0	10,0	12,0	14,0	16,0	17,9	19,9	21,9	23,9	25,9	27,9
	1,5	9,0	17,9	26,9	35,9	44,9	53,8	62,8	71,8	80,7	89,7	98,7	107,7	116,6	125,6
	2	16,0	31,9	47,9	63,8	79,8	95,7	111,7	127,6	143,6	159,5	175,5	191,4	207,4	223,3
	2,5	24,9	49,8	74,8	99,7	124,6	149,5	174,5	199,4	224,3	249,2	274,1	299,1	324,0	348,9
	3	35,9	71,8	107,7	143,6	179,4	215,3	251,2	287,1	323,0	358,9	394,8	430,7	466,5	502,4
	3,5	48,8	97,7	146,5	195,4	244,2	293,1	341,9	390,8	439,6	488,5	537,3	586,2	635,0	683,9
	4	63,8	127,6	191,4	255,2	319,0	382,8	446,6	510,4	574,2	638,0	701,8	765,6	829,4	893,2
	4,5	80,7	161,5	242,2	323,0	403,7	484,5	565,2	646,0	726,7	807,5	888,2	969,0	1049,7	1130,5
	5	99,7	199,4	299,1	398,8	498,4	598,1	697,8	797,5	897,2	996,9	1096,6	1196,3	1296,0	1395,7
	5,5	120,6	241,2	361,9	482,5	603,1	723,7	844,4	965,0	1085,6	1206,2	1326,9	1447,5	1500,0	1500,0
	6	143,6	287,1	430,7	574,2	717,8	861,3	1004,9	1148,4	1292,0	1435,5	1500,0	1500,0	1500,0	1500,0
	6,5	168,5	337,0	505,4	673,9	842,4	1010,9	1179,3	1347,8	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0
	7	195,4	390,8	586,2	781,6	977,0	1172,4	1367,7	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0
	7,5	224,3	448,6	672,9	897,2	1121,5	1345,8	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0
	8	255,2	510,4	765,6	1020,8	1276,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0
	8,5	288,1	576,2	864,3	1152,4	1440,5	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0
	9	323,0	646,0	969,0	1292,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0
	9,5	359,9	719,8	1079,6	1439,5	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0
	10	398,8	797,5	1196,3	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0
	11	439,6	879,3	1318,9	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0
	11	482,5	965,0	1447,5	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0
	12	527,4	1054,7	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0
	12	574,2	1148,4	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0
	13	623,1	1246,1	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0

Power matrix for Wello Penguin with 25 % power capture efficiency

	Te (s)														
		1,2	2,4	3,6	4,8	6	7,2	8,4	9,6	10,8	12	13,2	14,4	15,6	16,8
Hs (m)	0,5														
	1	1,7	3,3	5,0	6,6	8,3	10,0	11,6	13,3	15,0	16,6	18,3	19,9	21,6	23,3
	1,5	7,5	15,0	22,4	29,9	37,4	44,9	52,3	59,8	67,3	74,8	82,2	89,7	97,2	104,7
	2	13,3	26,6	39,9	53,2	66,5	79,8	93,0	106,3	119,6	132,9	146,2	159,5	172,8	186,1
	2,5	20,8	41,5	62,3	83,1	103,8	124,6	145,4	166,1	186,9	207,7	228,5	249,2	270,0	290,8
	3	29,9	59,8	89,7	119,6	149,5	179,4	209,3	239,3	269,2	299,1	329,0	358,9	388,8	418,7
	3,5	40,7	81,4	122,1	162,8	203,5	244,2	284,9	325,7	366,4	407,1	447,8	488,5	529,2	569,9
	4	53,2	106,3	159,5	212,7	265,8	319,0	372,2	425,3	478,5	531,7	584,8	638,0	691,2	744,4
	4,5	67,3	134,6	201,9	269,2	336,5	403,7	471,0	538,3	605,6	672,9	740,2	807,5	874,8	942,1
	5	83,1	166,1	249,2	332,3	415,4	498,4	581,5	664,6	747,7	830,7	913,8	996,9	1080,0	1163,0
	5,5	100,5	201,0	301,6	402,1	502,6	603,1	703,6	804,2	904,7	1005,2	1105,7	1206,2	1306,8	1407,3
	6	119,6	239,3	358,9	478,5	598,1	717,8	837,4	957,0	1076,7	1196,3	1315,9	1435,5	1500,0	1500,0
	6,5	140,4	280,8	421,2	561,6	702,0	842,4	982,8	1123,2	1263,6	1404,0	1500,0	1500,0	1500,0	1500,0
	7	162,8	325,7	488,5	651,3	814,1	977,0	1139,8	1302,6	1465,4	1500,0	1500,0	1500,0	1500,0	1500,0
	7,5	186,9	373,8	560,8	747,7	934,6	1121,5	1308,4	1495,3	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0
	8	212,7	425,3	638,0	850,7	1063,4	1276,0	1488,7	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0
	8,5	240,1	480,2	720,3	960,3	1200,4	1440,5	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0
	9	269,2	538,3	807,5	1076,7	1345,8	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0
	9,5	299,9	599,8	899,7	1199,6	1499,5	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0
	10	332,3	664,6	996,9	1329,2	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0
	11	366,4	732,7	1099,1	1465,4	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0
	11	402,1	804,2	1206,2	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0
	12	439,5	878,9	1318,4	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0
	12	478,5	957,0	1435,5	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0
	13	519,2	1038,4	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0	1500,0

APPENDIX 3. ONE STAGE INVESTMENT MODEL FOR WELLO PENGUIN

One phase investment scenario (per MW)															
Year	0	1	2	3	4	5	6	7	14	15	16	17	18	19	20
IC	-4434846														
O&M		-390581	-390581	-390580,8	-390581	-390581	-390581	-390580,82	-390581	-390581	-390581	-390581	-390581	-390580,82	-390581
Decommissioning															-65899,5
Mooring change								-285081,728	-327469						
Sales Profit		614040	614040	614040	614040	614040	614040	614040	614040	614040	614040	614040	614040	614040	614040
Annual profit (lost)	-4434846	223459,2	223459,2	223459,18	223459,2	223459,2	223459,2	-61622,5479	-104010	223459,2	223459,2	223459,2	223459,2	223459,18	157559,7
Annual disconted value	-4434846	212818,3	202684,1	193032,44	183840,4	175086,1	166748,7	-43793,9943	-52532,2	107487,7	102369,2	97494,5	92851,9	88430,38553	59382,59
Annual output MWh	2324,6		NPV/MW	-2 042 884											
FIT €/MWh	350		COE	443,4											
Years	20		IRR	-1,48 %											
Discount rate	5 %														
inflation rate	2 %														
WEC size, MW	1														
Number of WECs	100														
Farm size, MW	100														

PPENDIX 4. DECISION TREE RESULTS FOR BELMULLET AND M4

Decision tree analysis for Belmullet resource

		pospospos+	pospospos-	posposneg+	posposneg-	Posnegpos+	posnegpos-	posnegneg+	posnegneg-
		1	3	2	4	5	7	6	8
1st phase	NPV	-11 499 984	-11 499 984	-11 499 984	-11 499 984	-11 499 984	-11 499 984	-11 499 984	-11 499 984
	COE	424,77	424,77	424,77	424,77	424,77	424,77	424,77	424,77
	IRR	3,66 %	3,66 %	3,66 %	3,66 %	3,66 %	3,66 %	3,66 %	3,66 %
2nd phase	NPV	-59 802 315	-59 802 315	-59 802 315	-59 802 315	-81 804 186	-81 804 186	-81 804 186	-81 804 186
	COE	206,65	206,65	206,65	206,65	234,85	234,85	234,85	234,85
	IRR								
3rd phase	NPV	171 567 241	-32 079 386	123 001 471	-80 645 157	83 687 739	-119 958 889	25 635 022	-178 011 605
	COE	92,91	92,91	101,81	101,81	109,01	109,01	119,64	119,64
	IRR	12,83 %	4,53 %	10,48 %	2,62 %	8,85 %	1,26 %	6,83 %	

		negpospos+	negpospos-	Negposneg+	Negposneg-	negnegpos+	negnegpos-	negnegneg+	negnegneg-
		9	11	10	12	13	15	14	16
1st phase	NPV	-16 606 469	-16 606 469	-16 606 469	-16 606 469	-16 606 469	-16 606 469	-16 634 798	-16 606 469
	COE	457,96	457,96	457,96	457,96	457,96	457,96	458,15	457,96
	IRR	1,93 %	1,93 %	1,93 %	1,93 %	1,93 %	1,93 %	1,92 %	1,93 %
2nd phase	NPV	-85 202 990	-85 202 990	-85 202 990	-85 202 990	-97 846 210	-97 846 210	-97 862 502	-97 846 210
	COE	239,21	239,21	239,21	239,21	255,41	255,41	255,43	255,41
	IRR								
3rd phase	NPV	85 790 570	-117 856 058	50 403 580	-98 210 930	21 357 189	-182 289 439	-35 607 911	-239 242 497
	COE	108,62	108,62	119,80	119,80	120,43	120,43	130,86	130,86
	IRR	8,97 %	1,27 %	7,61 %	2,90 %	6,70 %		4,84 %	

		pospospos+	pospospos-	posposneg+	posposneg-	Posnegpos+	posnegpos-	posnegneg+	posnegneg-
		17	19	18	20	21	23	22	24
1st phase	NPV	-36 750 130	-36 750 130	-36 750 130	-36 750 130	-36 750 130	-36 750 130	-36 750 130	-36 750 130
	COE	588,93	588,93	588,93	588,93	588,93	588,93	588,93	588,93
	IRR								
2nd phase	NPV	-124 705 357	-124 705 357	-124 705 357	-124 705 357	-154 234 576	-154 234 576	-154 234 576	-154 234 576
	COE	289,84	289,84	289,84	289,84	327,68	327,68	327,68	327,68
	IRR								
3rd phase	NPV	-42 564 524	-246 211 152	-109 460 521	-313 107 148	-160 410 668	-364 057 295	-242 189 429	-445 836 056
	COE	132,13	132,13	144,39	144,39	153,72	153,72	168,70	168,70
	IRR	4,47 %		2,36 %		0,93 %			

		negpospos+	negpospos-	Negposneg+	Negposneg-	negnegpos+	negnegpos-	negnegneg+	negnegneg-
		25	27	26	28	29	31	30	32
1st phase	NPV	-43 877 085	-43 877 085	-43 877 085	-43 877 085	-43 877 085	-43 877 085	-43 877 085	-43 877 085
	COE	635,2614847	635,2614847	635,2614847	635,2614847	635,2614847	635,2614847	635,2614847	635,2614847
	IRR								
2nd phase	NPV	-158 988 287	-158 988 287	-158 988 287	-158 988 287	-178 214 589	-178 214 589	-178 214 589	-178 214 589
	COE	333,78	333,78	333,78	333,78	358,42	358,42	358,42	358,42
	IRR								
3rd phase	NPV	-159 003 042	-362 649 669	-219 497 788	-368 112 298	-255 172 328	-458 818 956	-337 549 885	-541 196 513
	COE	153,46	153,46	169,24	169,24	171,08	171,08	186,17	186,17
	IRR								

Decision tree analysis for M4 resource

		pospospos+	pospospos-	posposneg+	posposneg-	Posnegpos+	posnegpos-	posnegneg+	posnegneg-
		1	3	2	4	5	7	6	8
1st phase	NPV	-18 625 394	-18 625 394	-18 625 394	-18 625 394	-18 625 394	-18 625 394	-18 625 394	-18 625 394
	COE	489,56	489,56	489,56	489,56	489,56	489,56	489,56	489,56
	IRR	0,47 %	0,47 %	0,47 %	0,47 %	0,47 %	0,47 %	0,47 %	0,47 %
2nd phse	NPV	-74 412 096	-74 412 096	-74 412 096	-74 412 096	-96 413 966	-96 413 966	-96 413 966	-96 413 966
	COE	241,42	241,42	241,42	241,42	274,37	274,37	274,37	274,37
	IRR								
3rd phase	NPV	59 444 389	-110 565 383	10 878 618	-159 131 154	-28 435 113	-198 444 885	-86 487 830	-256 497 602
	COE	111,29	111,29	121,95	121,95	130,58	130,58	143,31	143,31
	IRR	8,52 %	0,43 %	6,42 %		4,96 %		2,98 %	
		negpospos+	negpospos-	Negposneg+	Negposneg-	negnegpos+	negnegpos-	negnegneg+	negnegneg-
		5	5	6	6	7	7	8	8
1st phase	NPV	-23 731 879	-23 731 879	-23 731 879	-23 731 879	-23 731 879	-23 731 879	-23 760 207	-23 731 879
	COE	527,83	527,83	527,83	527,83	527,83	527,83	528,04	527,83
	IRR								
2nd phse	NPV	-99 812 770	-99 812 770	-99 812 770	-99 812 770	-112 455 991	-112 455 991	-112 472 283	-112 455 991
	COE	279,46	279,46	279,46	279,46	298,39	298,39	298,42	298,39
	IRR								
3rd phase	NPV	-26 332 282	-196 342 054	-65 951 950	-190 019 405	-90 765 664	-260 775 435	-147 730 764	-317 728 494
	COE	130,11	130,11	143,50	143,50	144,25	144,25	156,75	156,75
	IRR	5,02 %		3,73 %		2,77 %		0,72 %	
		pospospos+	pospospos-	posposneg+	posposneg-	Posnegpos+	posnegpos-	posnegneg+	posnegneg-
		17	19	18	20	21	23	22	24
1st phase	NPV	-36 750 130	-43 875 540	-43 875 540	-43 875 540	-43 875 540	-43 875 540	-43 875 540	-43 875 540
	COE	588,93	678,77	678,77	678,77	678,77	678,77	678,77	678,77
	IRR								
2nd phse	NPV	-124 705 357	-139 315 138	-139 315 138	-139 315 138	-168 844 356	-168 844 356	-168 844 356	-168 844 356
	COE	289,84	338,61	338,61	338,61	382,83	382,83	382,83	382,83
	IRR								
3rd phase	NPV	-42 564 524	-324 697 148	-221 583 373	-391 593 145	-272 533 520	-442 543 292	-354 312 281	-524 322 053
	COE	132,13	158,28	172,95	172,95	184,13	184,13	202,08	202,08
	IRR	4,47 %							
		negpospos+	negpospos-		Negposneg-	negnegpos+	negnegpos-	negnegneg+	negnegneg-
		25	27	26	28	29	31	30	32
1st phase	NPV	-51 002 495	-51 002 495	-51 002 495	-51 002 495	-51 002 495	-51 002 495	-51 002 495	-51 002 495
	COE	732,1692705	732,1692705	732,1692705	732,1692705	732,1692705	732,1692705	732,1692705	732,1692705
	IRR								
2nd phse	NPV	-173 598 068	-173 598 068	-173 598 068	-173 598 068	-192 824 370	-192 824 370	-192 824 370	-192 824 370
	COE	389,95	389,95	389,95	389,95	418,74	418,74	418,74	418,74
	IRR								
3rd phase	NPV	-271 125 894	-441 135 666	-335 853 318	-459 920 773	-367 295 181	-537 304 953	-449 672 738	-619 682 509
	COE	183,82	183,82	202,72	202,72	204,92	204,92	223,00	223,00
	IRR								